Joint Centre for Mesoscale Meteorology, Reading, UK

A JCMM Overview of FASTEX IOPS

S. A. Clough
H. W. Lean
N. M. Roberts
H. Birkett
J. P. Chaboureau
R. Dixon
M. Griffiths
T. D. Hewson
A. Montani

Internal Report No. 81

January 1998

Met Office Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
www.metoffice.com

Designed and produced by the Met Office © Crown copyright 2001 01/0240 The Met Office logo is a registered trademark.

A JCMM OVERVIEW OF FASTEX IOPS

by

S A Clough[1*], H W Lean[*], N M Roberts[*], H Birkett[**],
J-P Chaboureau[**], R Dixon[**], M Griffiths[**],
T D Hewson[*] and A Montani[**]

Joint Centre for Mesoscale Meteorology,
[*]UK Meteorological Office/[**]University of Reading, UK

January 1998

INTERNAL REPORT NO.81

A JCMM OVERVIEW OF FASTEX IOPS

by

S A Clough[1*], H W Lean[*], N M Roberts[*], H Birkett[**], J-P Chaboureau[**], R Dixon[**], M Griffiths[**], T D Hewson[*] and A Montani[**]

[*] Joint Centre for Mesoscale Meteorology,
[*] UK Meteorological Office/ [**] University of Reading, UK

SUMMARY

The Fronts and Atlantic Storm Track Experiment (FASTEX) took place through January and February 1997. The experiment had two principal objectives. The first was to observe the evolution of a group of cyclonic weather systems from the US Eastern seaboard across to the Eastern Atlantic and thus provide a test of methods of optimising forecasts by appropriate targeting of upstream observations. The second objective was to observe the mesoscale structure of oceanic weather systems in unprecedented detail by combined use of airborne Doppler radar and dropsonde observations. The experiment was particularly successful and resulted in observations of 20 weather events.

Given the difficulty of carrying out scientific studies of so many events, it was necessary to evaluate, compare and prioritise them. During April 1997 several JCMM members took part in an internal workshop to provide a timely evaluation of the Intensive Observing Periods (IOPs) from the point of view of JCMM's own scientific goals. This report summarises the main conclusions of the workshop regarding the evolution, distribution of observations and perceived scientific value of the individual cases. It includes brief summaries of observation distributions and tables comparing morphology, development, tropopause structure and diabatic process information for the systems observed. A fuller form also exists as a set of JCMM WWW pages (http://www.met.rdg.ac.uk/FASTEX), including animations of the events. The intention is not to give a comprehensive final account, but to give a brief account of the main aspects of the cases as an initial guide to further study.

1. INTRODUCTION

The Fronts and Atlantic Storm Track Experiment (FASTEX) was carried out during January and February 1997. The experiment was the most ambitious attempt to date to document the life history and structure of developing mid-latitude frontal systems over the data-sparse oceans (Joly et al, 1997). A central part of the experiment was the involvement of 7 research aircraft and 4 ships (Knorr, Victor Bugaev, Aegir, and Şuroit) to provide dropsonde, radiosonde and other observations with high resolution. The experiment was

led by an international scientific team based at Shannon Airport in the west of Ireland. Shannon was also the main operating base for 3 of the aircraft (NOAA P3, Gulf Stream IV (G-IV) and NCAR Electra). The remaining aircraft were based at Lyneham, UK (UK C-130) and St Johns, Newfoundland (Lear Jet and, for a brief period, 2 US C-130s). Jorgensen et al (1996) provides the detailed Operations Plan for the experiment including much of the notation used below, and information provided in this and Joly et al (1997) provide useful background to the material given below.

The experiment comprised two main stages (Fig 1): an Upstream experiment (in the Far Upstream Area (FUS) and Near Upstream Area (NUS)) to observe the early stages of development in the Atlantic west of 25W and a Multiscale Sampling Area (MSA) east of 25W. These areas are frequently referred to in the information given below. The Lear Jet and US C-130 aircraft made dropsonde observations primarily in the FUS, while the UK C-130, P3 and Electra aircraft carried out high resolution dropsonde and Doppler radar observations in the MSA. The GIV, meanwhile, made dropsonde observations in the FUS, NUS and MSA areas.

The authors were participants in a workshop which was carried out within JCMM to evaluate the cases from the point of view of JCMM's research priorities[1]. The process of evaluation was broken into 2 main stages: to provide first level overviews of all cases, then more detailed study of some observations for the 9 major cases.

In the first stage the group worked in pairs for about a week to review 5 or so IOPs each. These reviews included

- Production of (48hr or so) animations of (a) satellite imagery with surface pressure and objective frontal analyses (Hewson (1966)) (b) 700mb vertical velocity with surface pressure and height of the potential vorticity (PV) =2PVU surface superimposed to provide an overview of the development (c) other animations as deemed necessary to distinguish e.g. ana/kata frontal and other characteristics of interest. Animations (a) and (b) are retained on web pages. Single frames from (a) are shown in Section 2 for each IOP; these generally correspond to MSA mid-flight times.

- Preparation of diagrams summarising special observations for each IOP, which are given in Section 2.

- Preparation of 1-page summary lists setting out the type of system observed, observations, meteorological features of interest and important limitations. These are presented in Section 2. These summaries were prepared mainly on the basis of data available within the UK Met. Office, including :

  Real time dropsonde information
  Diagnostic information from the UKMO Limited Area Model (LAM)
  Meteosat imagery from the UKMO Autosat system
  Sferics (lightning reports) from the UKMO ATD Sferics system
  Miscellaneous sounding and other data

[1] Thus although it may provide useful guidance for other studies this should be borne in mind in using this document.

- Preparation of tables with information pertaining to different aspects of weather system study. These are presented in Section 3. The tabulated quantities should allow the reader to identify features of interest within the following topic areas :

  Basic Information
  Development
  Morphology
  Tropopause Structure
  Diabatic Processes
  Fronts
  Forecast Accuracy in the UK Met. Office Unified Model

The above results were presented in a plenary session and the scientific interest in cases assessed using two 5-point scales, one for perceived upstream forecasting interest and the second for mesoscale study, given the available data. For interest, these are given in Section 3, though clearly such indices are highly subjective, and should not be regarded as definitive. They primarily reflect JCMM's own research interest in the cases, and even the lower rated cases were in some respects more completely observed than most previous studies.

The cases agreed to be most important were subjected to the more detailed reviewing stage, concentrating upon features remarked upon in the first stage. This second stage was carried out also with reference to cross-sections and other products from dropsonde data produced in real time (without full quality controls applied) and further UKMO LAM analysis and forecast fields. Conclusions from the second stage have been incorporated into the one-page summaries for each IOP given in Section 2.

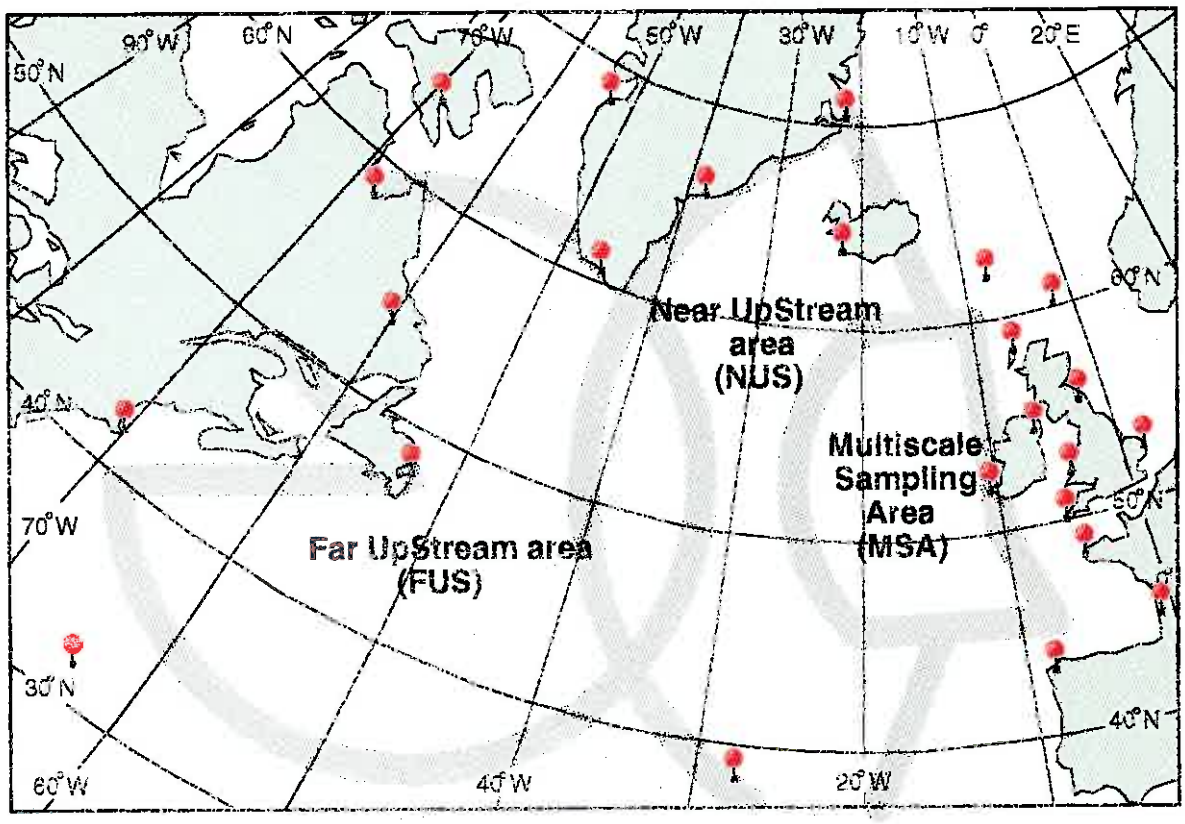
- Preparation of tables with information pertaining to different aspects of weather system study. These are presented in Section 3. The tabulated quantities should allow the reader to identify features of interest within the following topic areas :

  Basic Information
  Development
  Morphology
  Tropopause Structure
  Diabatic Processes
  Fronts
  Forecast Accuracy in the UK Met. Office Unified Model

The above results were presented in a plenary session and the scientific interest in cases assessed using two 5-point scales, one for perceived upstream forecasting interest and the second for mesoscale study, given the available data. For interest, these are given in Section 3, though clearly such indices are highly subjective, and should not be regarded as definitive. They primarily reflect JCMM's own research interest in the cases, and even the lower rated cases were in some respects more completely observed than most previous studies.

The cases agreed to be most important were subjected to the more detailed reviewing stage, concentrating upon features remarked upon in the first stage. This second stage was carried out also with reference to cross-sections and other products from dropsonde data produced in real time (without full quality controls applied) and further UKMO LAM analysis and forecast fields. Conclusions from the second stage have been incorporated into the one-page summaries for each IOP given in Section 2.

Figure 1. Key notation used in the following observation summaries



Sites where radiosondes are released at 6 hourly or more frequent intervals.

FASTEX ships releasing radiosondes.

Other ships releasing radiosondes.

Aircraft flight tracks - colour coded Lear Jet, G-IV, UK-C130, P3, Electra
The colour of US C-130 tracks varies. Other additional colours are used for G-IV flight tracks when there was more than one flight during an IOP.

Track of the low pressure centre.

The position of the low at the time of the infrared image.

2. IOP SUMMARIES

a) The IOPs

IOP1 Systematic survey of transient frontal wave low within a low pressure complex

IOP2 Phenomenon investigation of warm sector wave in meridional flow

IOP3 Interaction of a trough drifting southwards and a wave on a cold front

IOP4 A cold-air comma cloud system moving slowly into the SW part of the MSA

IOP5 Development of a cyclone, the rearmost of two on a trailing cold front

IOP6 Intense north-south oriented front without waves in the MSA

IOP7 Flat Frontal Wave translating rapidly NE through Western Half of MSA

IOP8 Downslope wave phenomenon to the lee of Greenland (Non FASTEX case)

IOP9 Large, well developed cyclone. Second deepening phase near Iceland

IOP10 Frontal wave with strong convection and no closed circulation

IOP11 Primary cyclone forming over E America and deepening while crossing the Atlantic

IOP11A Developing cold frontal wave - classic example of a FASTEX cyclone

IOP12 Investigation of Explosive Cyclogenesis

IOP13 Decaying mature wave heading towards Northern Britain

IOP14 Slowly weakening, elongated low

IOP15 Excellent 3-arc systematic survey of mature cyclone occlusion in the MSA

IOP16 Fast moving, rapidly deepening, secondary wave cyclone

IOP17 The "FASTEX CYCLONE": explosively deepening col wave

IOP18 Good life-cycle coverage of explosive cyclonic development in cold air

IOP19 Very weak open wave on the trailing cold front of a primary cyclone

2. IOP SUMMARIES

a) The IOPs

IOP1 Systematic survey of transient frontal wave low within a low pressure complex

IOP2 Phenomenon investigation of warm sector wave in meridional flow

IOP3 Interaction of a trough drifting southwards and a wave on a cold front

IOP4 A cold-air comma cloud system moving slowly into the SW part of the MSA

IOP5 Development of a cyclone, the rearmost of two on a trailing cold front

IOP6 Intense north-south oriented front without waves in the MSA

IOP7 Flat Frontal Wave translating rapidly NE through Western Half of MSA

IOP8 Downslope wave phenomenon to the lee of Greenland (Non FASTEX case)

IOP9 Large, well developed cyclone. Second deepening phase near Iceland

IOP10 Frontal wave with strong convection and no closed circulation

IOP11 Primary cyclone forming over E America and deepening while crossing the Atlantic

IOP11A Developing cold frontal wave - classic example of a FASTEX cyclone

IOP12 Investigation of Explosive Cyclogenesis

IOP13 Decaying mature wave heading towards Northern Britain

IOP14 Slowly weakening, elongated low

IOP15 Excellent 3-arc systematic survey of mature cyclone occlusion in the MSA

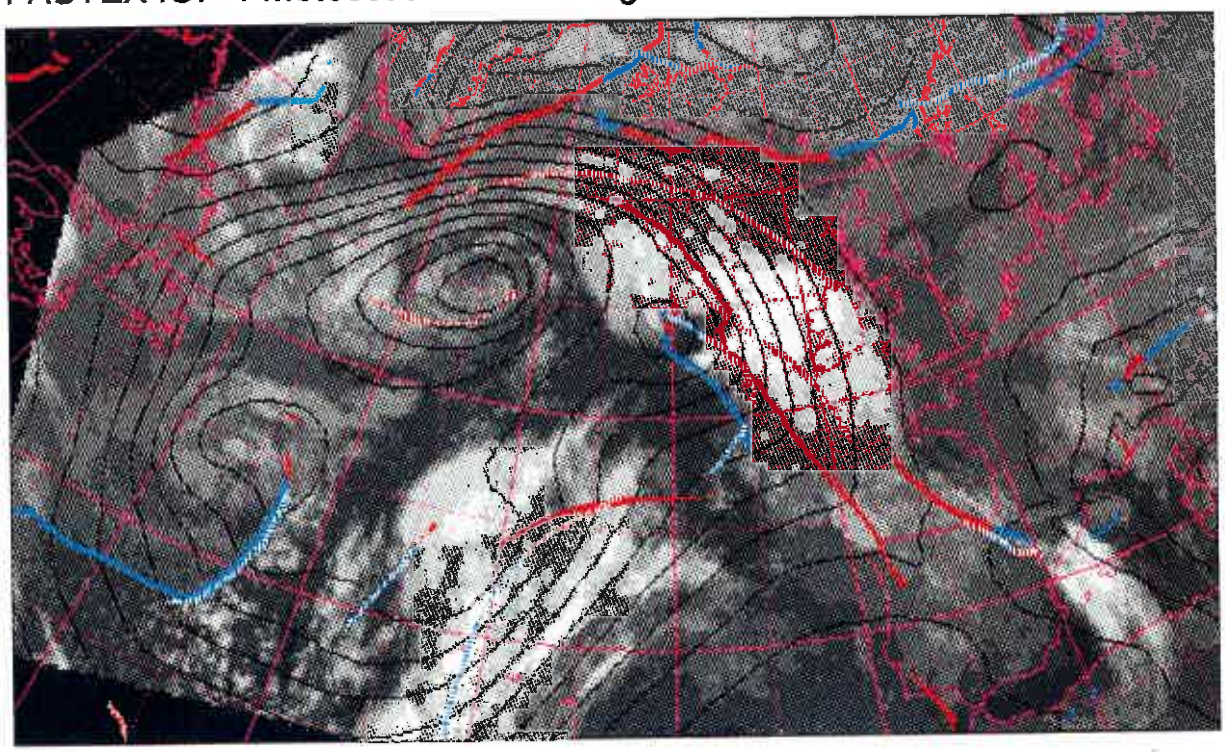
IOP16 Fast moving, rapidly deepening, secondary wave cyclone

IOP17 The "FASTEX CYCLONE": explosively deepening col wave

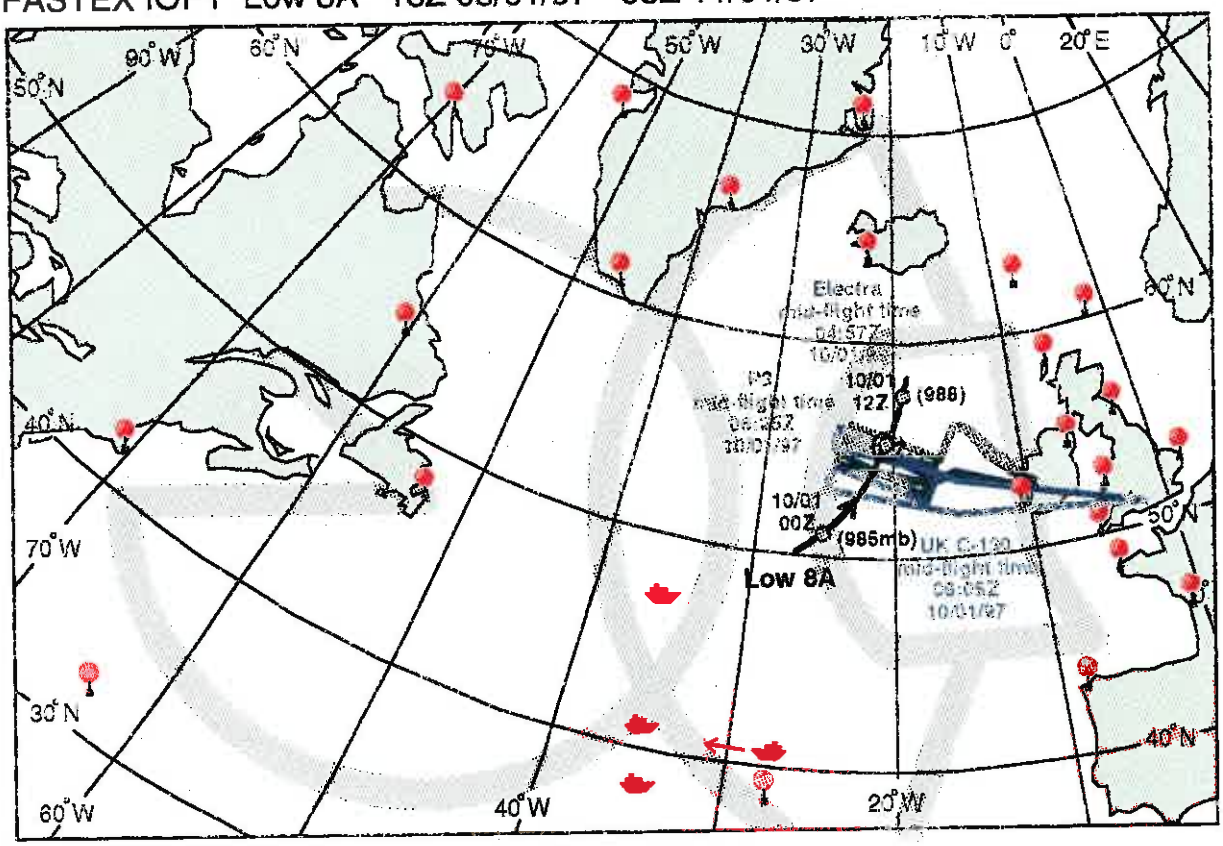
IOP18 Good life-cycle coverage of explosive cyclonic development in cold air

IOP19 Very weak open wave on the trailing cold front of a primary cyclone

FASTEX IOP 1 Meteosat infrared image 12Z 10/01/97



FASTEX IOP1 Low 8A 18Z 08/01/97 - 06Z 11/01/97



b) IOP Summaries

IOP1 - LOW 8A 8-10 JAN 1997

Systematic survey of transient frontal wave low on a cloud complex forming in the MSA

Cloud head and dry intrusion observed with radar and dropsondes

Observations :

Aircraft: Upstream: None

MSA: UK C-130 (flight A506, 40 LORAN[2] sondes), P-3 and Electra

Ships: 3 + 1 moving into position

Additional soundings: Upstream North America, Europe coastal

Meteorology of Interest :

Short wave north-south pattern, upstream tough/ridge observed by MSA aircraft

Systematic survey of cloud head and dry intrusion

Early development in ship area captured

Limitations :

Unsuitable for upstream observing or continuity-based studies

MSA observations in a region of complex frontal structure

[2] For most of FASTEX GPS dropsondes were used, from which winds are determined using retransmitted Global Positioning System signals. For IOPs 1, 2 and 7, however, the UK C-130 used older dropsondes from which less accurate winds were determined using retransmitted positions from the LORAN-C navigation system.

b) IOP Summaries

IOP1 - LOW 8A 8-10 JAN 1997

Systematic survey of transient frontal wave low on a cloud complex forming in the MSA

Cloud head and dry intrusion observed with radar and dropsondes

Observations :

Aircraft: Upstream: None

MSA: UK C-130 (flight A506, 40 LORAN[2] sondes), P-3 and Electra

Ships: 3 + 1 moving into position

Additional soundings: Upstream US, Europe coastal

Meteorology of Interest :

Short wave north-south pattern, upstream tough/ridge observed by MSA aircraft

Systematic survey of cloud head and dry intrusion

Early development in ship area captured

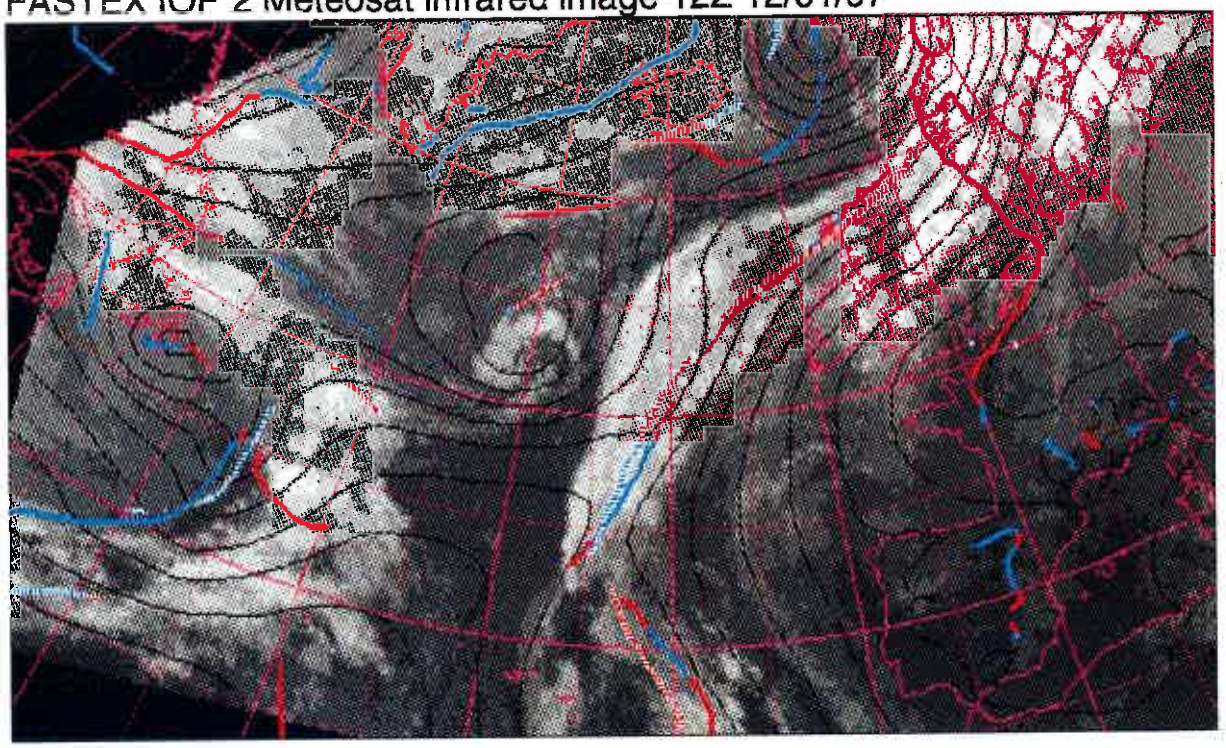
Limitations :

Unsuitable for upstream observing or continuity-based studies

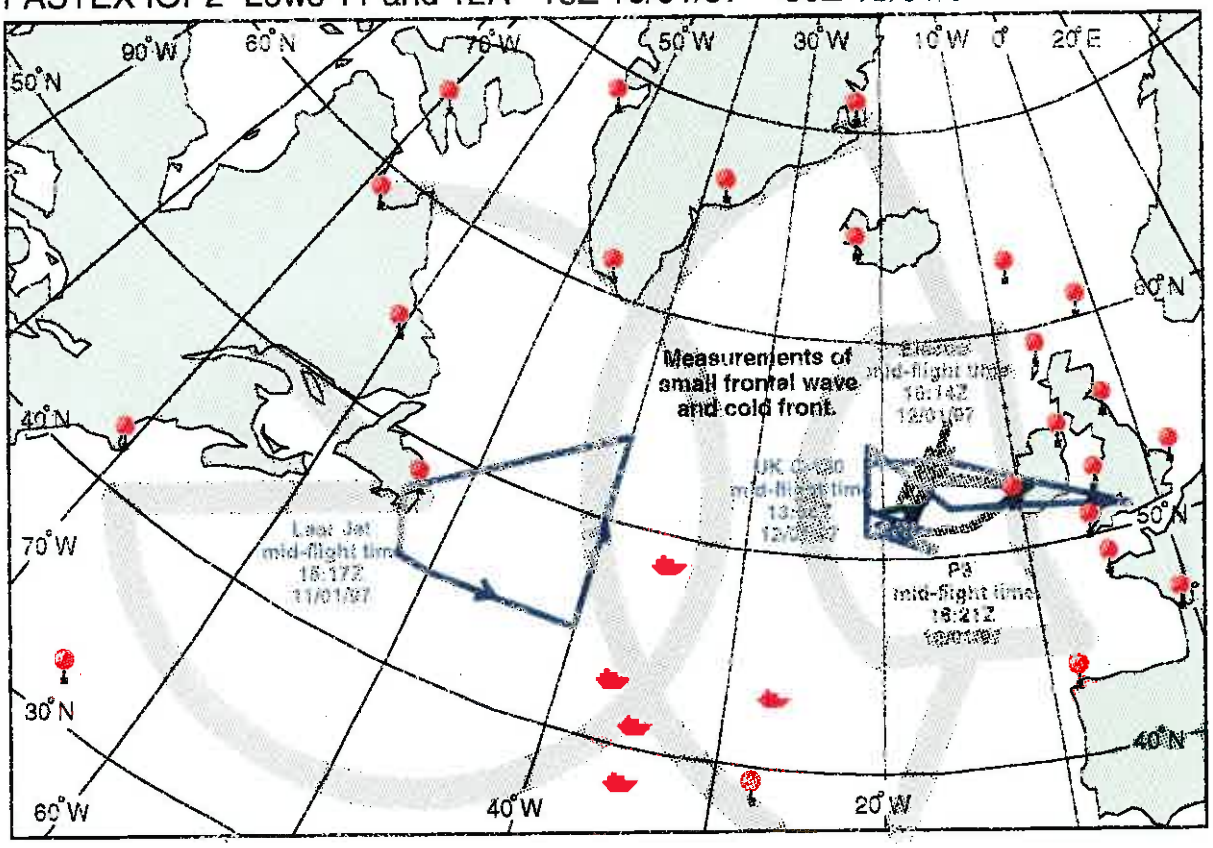
MSA observations in a region of complex frontal structure

[2] For most of FASTEX GPS dropsondes were used, from which winds are determined using retransmitted Global Positioning System signals. For IOPs 1, 2 and 7, however, the UK C-130 used older dropsondes from which less accurate winds were determined using retransmitted positions from the LORAN-C navigation system.

FASTEX IOP 2 Meteosat infrared image 12Z 12/01/97



FASTEX IOP2 Lows 11 and 12A 15Z 10/01/97 - 00Z 13/01/97



IOP 2 - LOW 11/12A 11-12 JAN 1997

Phenomenon investigation of warm sector wave in meridional flow

Narrow cold frontal rainbands well observed with radar and dropsondes

Observations :

Aircraft: Upstream: Lear

MSA : UK C-130 (40 sondes, no winds), P3 and Electra

Ships: 4

Additional soundings: Upstream North America, Europe coastal

Meteorology of Interest :

Classic cold front environment with narrow bands observed by Doppler radar aircraft

Thermodynamic structure observed during MSA flights is probably symptomatic of sublimation effects

Lear Jet observations appear close to MSA post-frontal airmass

Limitations :

UK C-130 dropsondes no winds

IOP 2 - LOW 11/12A 11-12 JAN 1997

Phenomenon investigation of warm sector wave in meridional flow

Narrow cold frontal rainbands well observed with radar and dropsondes

Observations :

Aircraft: Upstream: Lear

MSA : UK C-130 (40 sondes, no winds), P3 and Electra

Ships: 4

Additional soundings: Upstream US, Europe coastal

Meteorology of Interest :

Classic cold front environment with narrow bands observed by Doppler radar aircraft

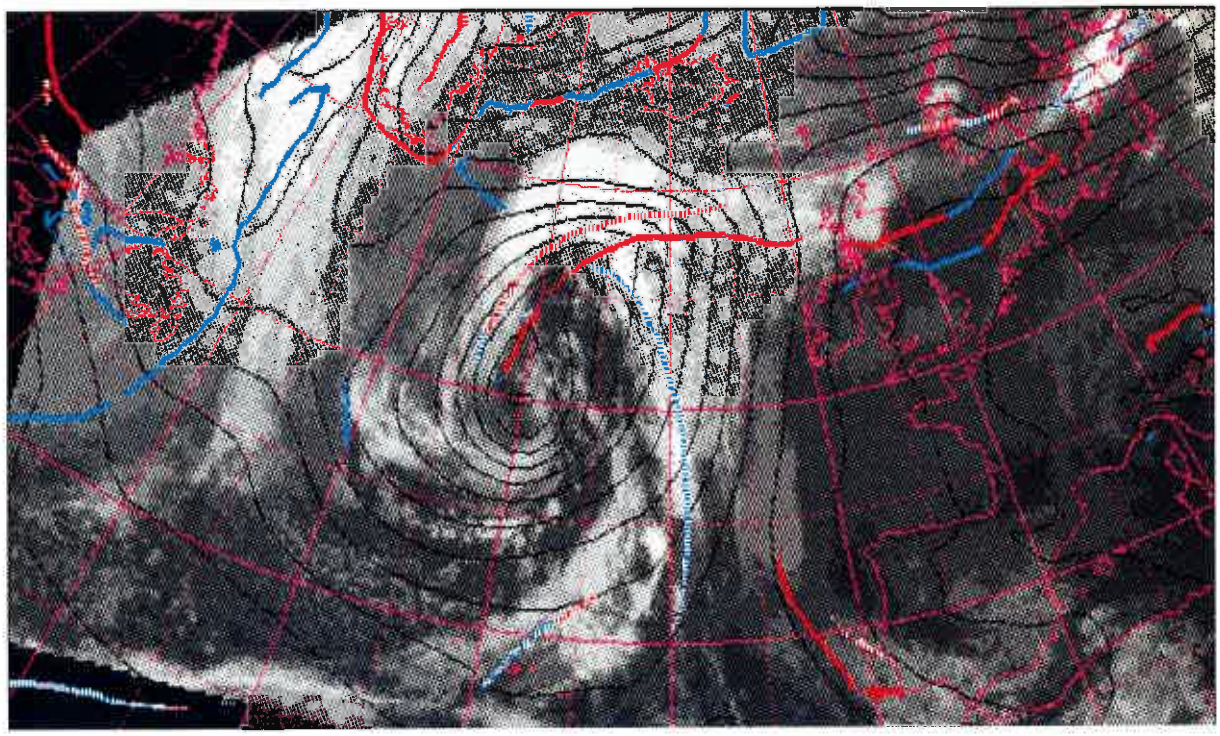
Thermodynamic structure observed during MSA flights is probably symptomatic of sublimation effects

Lear Jet observations appear close to MSA post-frontal airmass

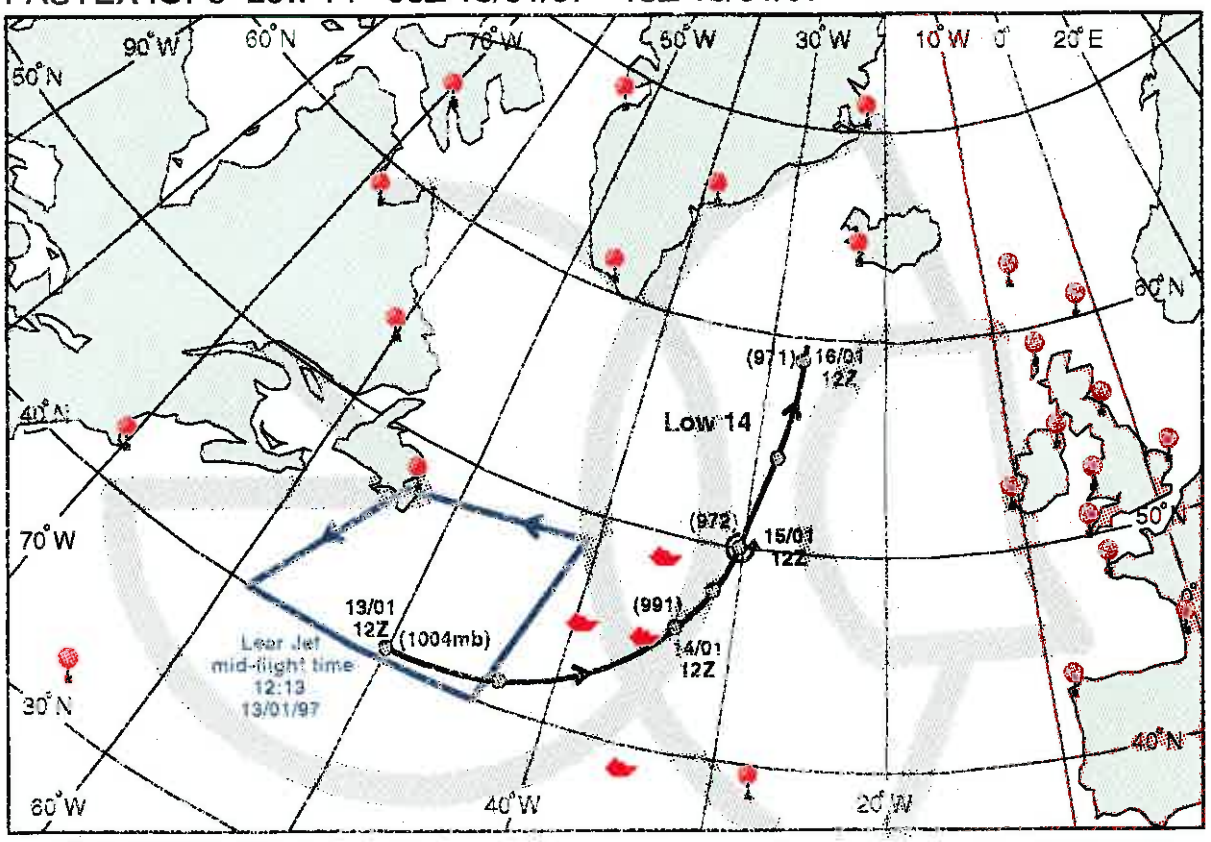
Limitations :

UK C-130 dropsondes no winds

FASTEX IOP 3 Meteosat infrared image 12Z 15/01/97



FASTEX IOP3 Low 14 06Z 13/01/97 - 18Z 16/01/97



IOP 3 - LOW 14 13-16 JAN 1997

Development of a large mature low in mid-Atlantic

Interaction of a trough drifting southwards and a wave on the cold front trailing back from low 13, while low 14A was following closely behind

The precursors of the double system (low 14/14A) were investigated by a Lear Jet upstream flight (t/o 13th Jan, a.m.), which captured the cold front of low 13

Observations :

Aircraft: Upstream: Lear

Ships: 4 (good coverage, including excellent sea surface flux measurements in high winds by R.V. Knorr)

Additional soundings: Upstream North America, Europe coastal

Meteorology of Interest :

Interaction between upper trough and a wave on the cold front

Large ECMWF model errors

Limitations :

System tracked north-eastwards, too far to be properly verified by the turbo-props

IOP 3 - LOW 14 13-16 JAN 1997

Development of a large mature low in mid-Atlantic

Interaction of a trough drifting southwards and a wave on the cold front trailing back from low 13, while low 14A was following closely behind

The precursors of the double system (low 14/14A) were investigated by a Lear Jet upstream flight (t/o 13th Jan, a.m.), which captured the cold front of low 13

Observations :

Aircraft: Upstream: Lear

Ships: 4 (good coverage, including excellent sea surface flux measurements in high winds by R.V. Knorr)

Additional soundings: Upstream US, Europe coastal

Meteorology of Interest :

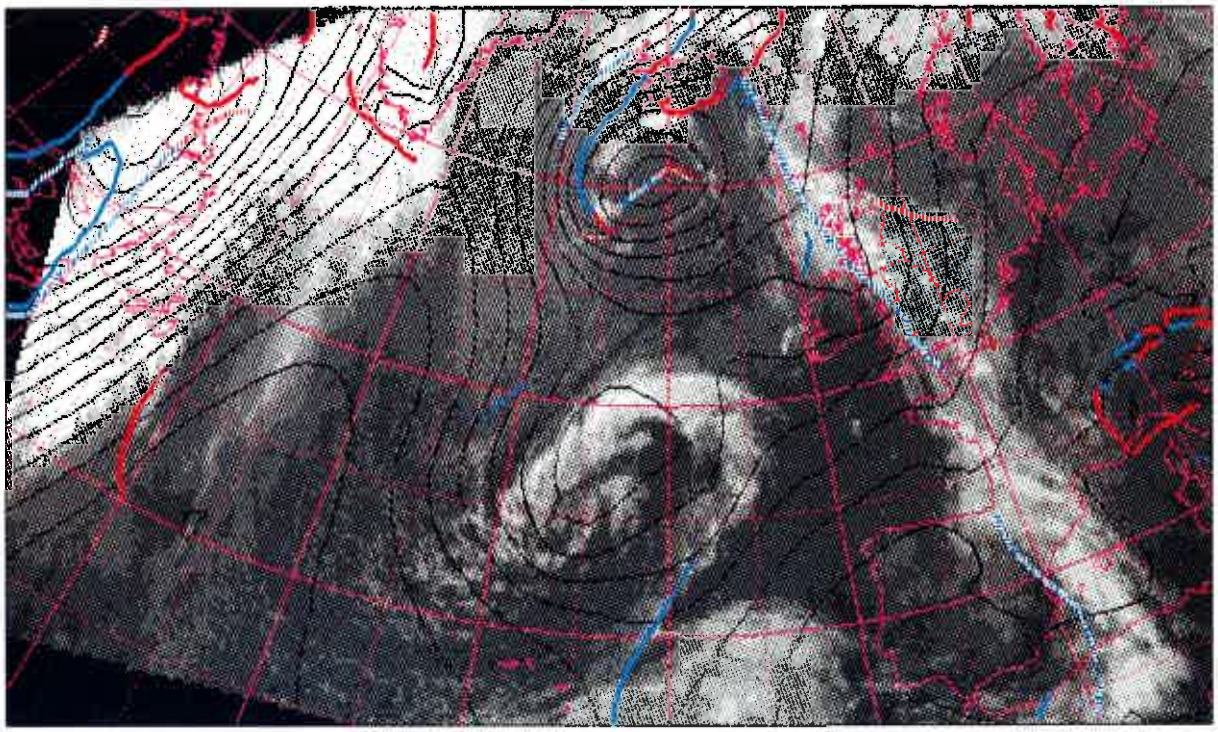
Interaction between upper trough and a wave on the cold front

Large ECMWF model errors

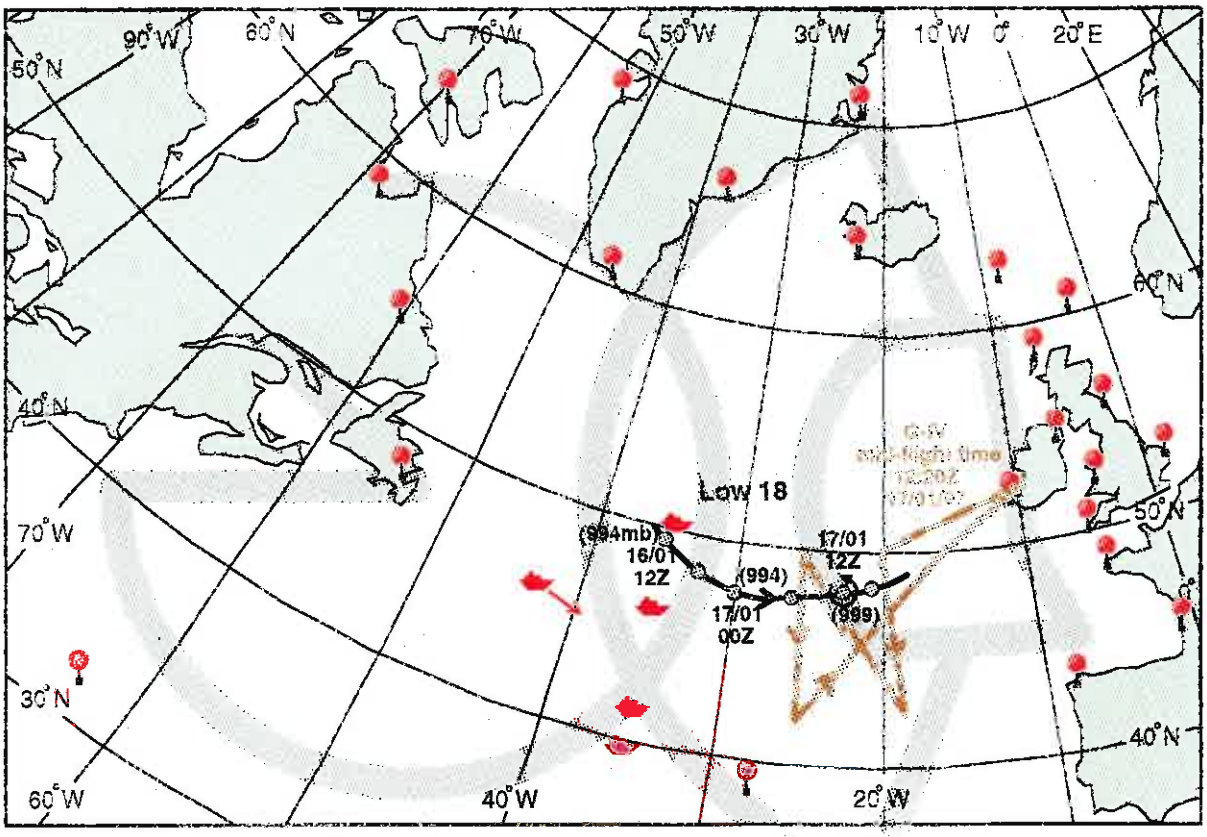
Limitations :

System tracked north-eastwards, too far to be properly verified by the turbo-props

FASTEX IOP 4 Meteosat infrared image 12Z 17/01/97



FASTEX IOP4 Low 18 06Z 16/01/97 - 12Z 19/01/97



IOP 4 - LOW 18 16-19 JAN 1997

A cold-air comma cloud system moving slowly into the SW part of the MSA

Observations :

Aircraft: MSA: G-IV (NUS flight combined)

Upstream: 4 ships (particularly useful data since system moving slowly)

Additional soundings: None

Meteorology of Interest :

Cold air feature

Not rapidly deepening

Does not develop on frontal zone

Comma cloud (1000km approx diameter in imagery)

Mesoscale vortices in low suggested by cloud hooks

Convection, sferics in vicinity of dropsoundings

Distinct upper level PV anomaly - largely upper level forced

Associated dry intrusion

300mb PV min ahead

Weak low level thermal gradient

Limitations :

No baroclinity - not a FASTEX-type cyclone

Only G-IV aircraft observations

IOP 4 - LOW 18 16-19 JAN 1997

A cold-air comma cloud system moving slowly into the SW part of the MSA

Observations :

Aircraft: MSA: G-IV (NUS flight combined)

Upstream: 4 ships (particularly useful data since system moving slowly)

Additional soundings: None

Meteorology of Interest :

Cold air feature

Not Rapidly Deepening

Does not develop on frontal zone

Comma Cloud (1000km approx diameter in imagery)

Mesoscale vortices in low suggested by cloud hooks

Convection, sferics in vicinity of dropsoundings

Distinct upper level PV anomaly - largely upper level forced

Associated dry intrusion

300mb PV min ahead

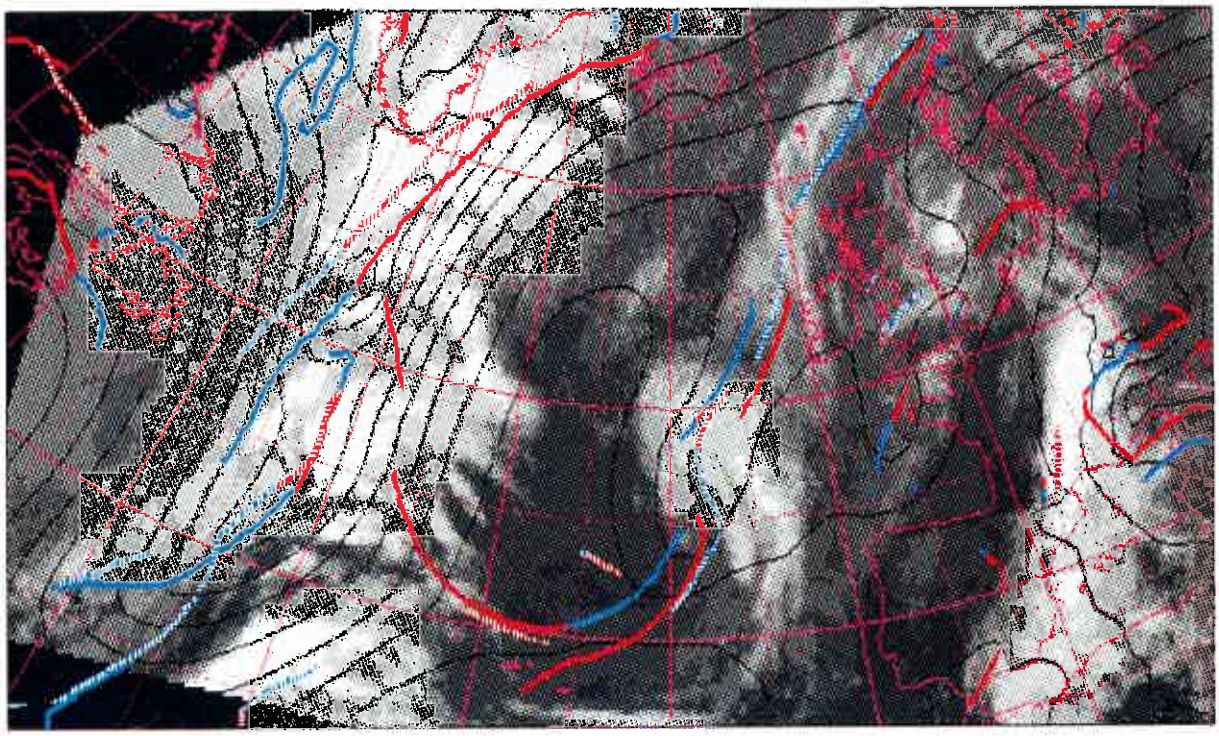
Weak low level thermal gradient

Limitations :

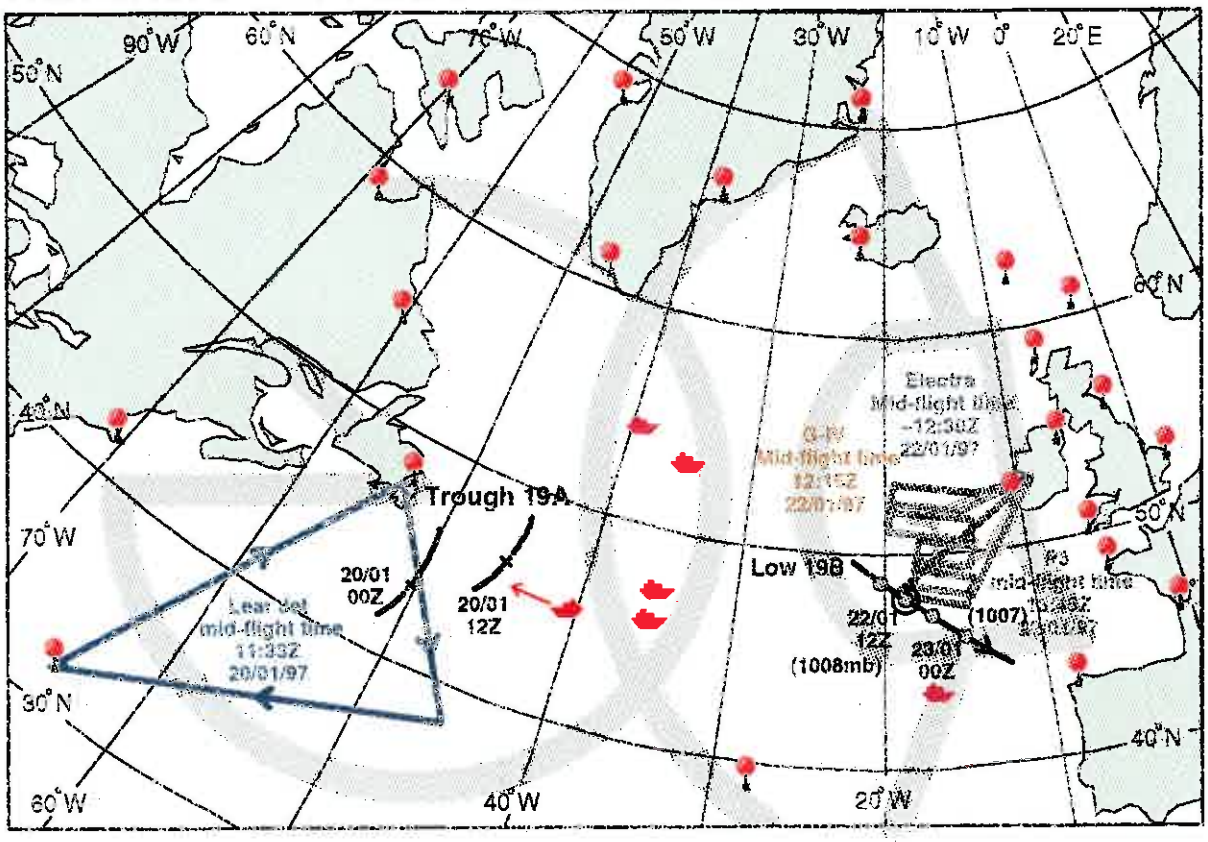
No baroclinity - not a FASTEX-type cyclone

Only G-IV aircraft observations

FASTEX IOP 5 Meteosat infrared image 12Z 22/01/97



FASTEX IOP5 Lows 19A and 19B 12Z 19/01/97 - 00Z 23/01/97



IOP 5 - LOW 19A/B 19-22 JAN 1997

Two cyclones (low 19A, 19B) developed on the trailing cold front of low 19

The second low developed in preference to the first

Upper level anomaly interacting, briefly, with low level front between highs

Observations :

Aircraft: Upstream: Lear

MSA: P3, Electra, G-IV, UK C-130 (flight A509)

Ships: 4

Additional soundings: North America-coastal

Meteorology of Interest :

Intense convective rainbands observed on the edge of an intruding dry slot

Lear flight may have sampled upper level PV anomaly

Limitations :

UK-C-130 GPS dropsonde flight aborted

Flights restricted to southern limit of 47N

IOP 5 - LOW 19A/B 19-22 JAN 1997

Two cyclones (low 19A, 19B) developed on the trailing cold front of low 19

The second low developed in preference to the first

Upper level anomaly interacting, briefly, with low level front between highs

Observations :

Aircraft: Upstream: Lear

MSA: P3, Electra, G-IV, UK C-130 (flight A509)

Ships: 4

Additional soundings: US-coastal

Meteorology of Interest :

Intense convective rainbands observed on the edge of an intruding dry slot

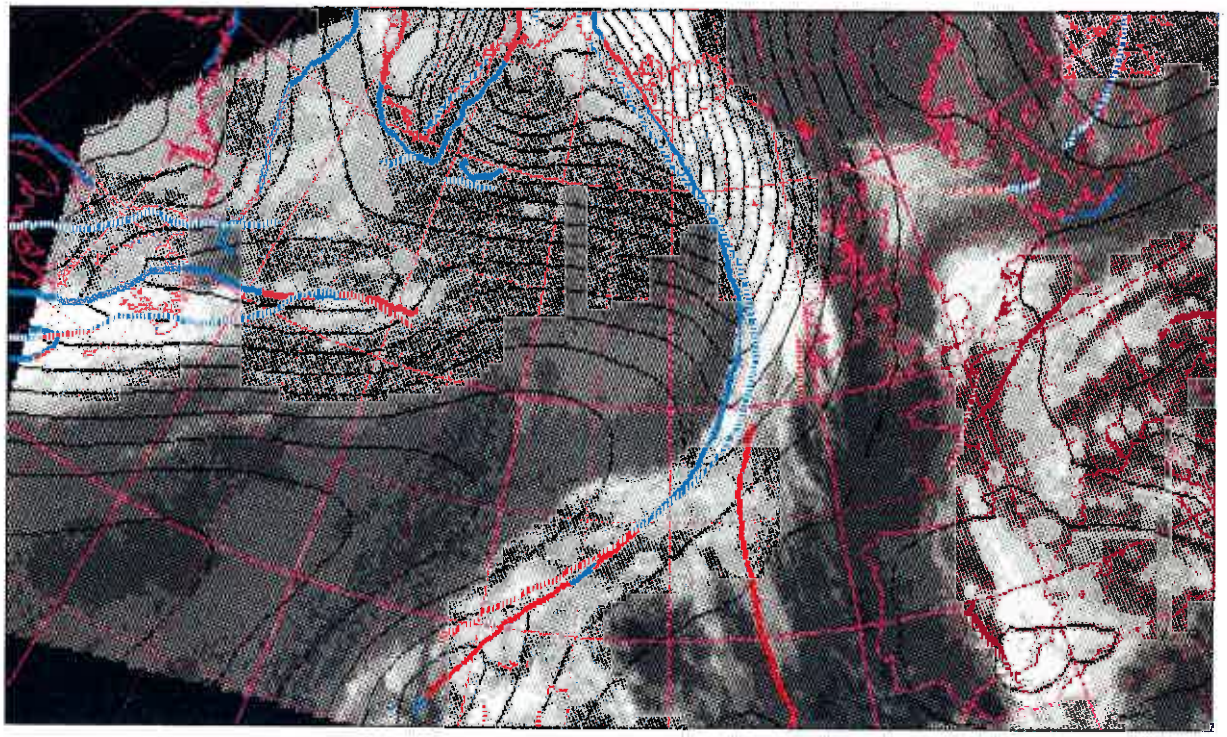
Lear flight may have sampled upper level PV anomaly

Limitations :

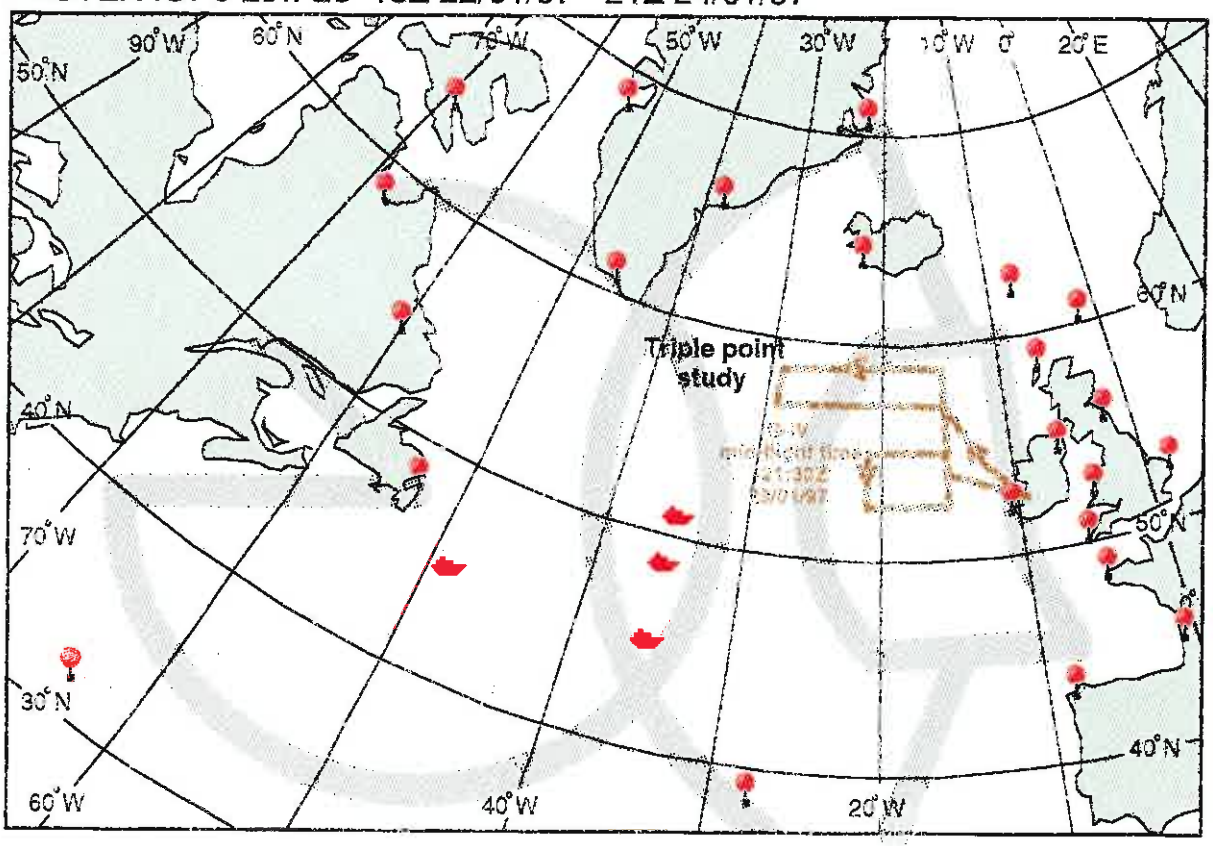
UK-C-130 GPS dropsonde flight aborted

Flights restricted to southern limit of 47N

FASTEX IOP 6 Meteosat infrared image 21Z 23/01/97



FASTEX IOP6 Low 20 15Z 22/01/97 - 21Z 24/01/97



IOP6 - LOW 20 22-24 JAN 1997

Intense north-south front without waves in the MSA. Observations of high PV filament structure from Eire and UK

Observations :

Aircraft: Upstream: G-IV (NUS)

MSA: G-IV

Ships: 4

Additional soundings: Upstream North America (short period), Europe coastal

Meteorology of Interest :

Tropopause structure - PV, ozone, Aberystwyth MST radar

Limitations :

Limited data range especially in MSA

IOP6 - LOW 20 22-24 JAN 1997

Intense north-south front without waves in the MSA. Observations of high PV filament structure from Eire and UK

Observations :

Aircraft: Upstream: G-IV (NUS)

MSA: G-IV

Ships: 4

Additional soundings: Upstream US (short period), Europe coastal

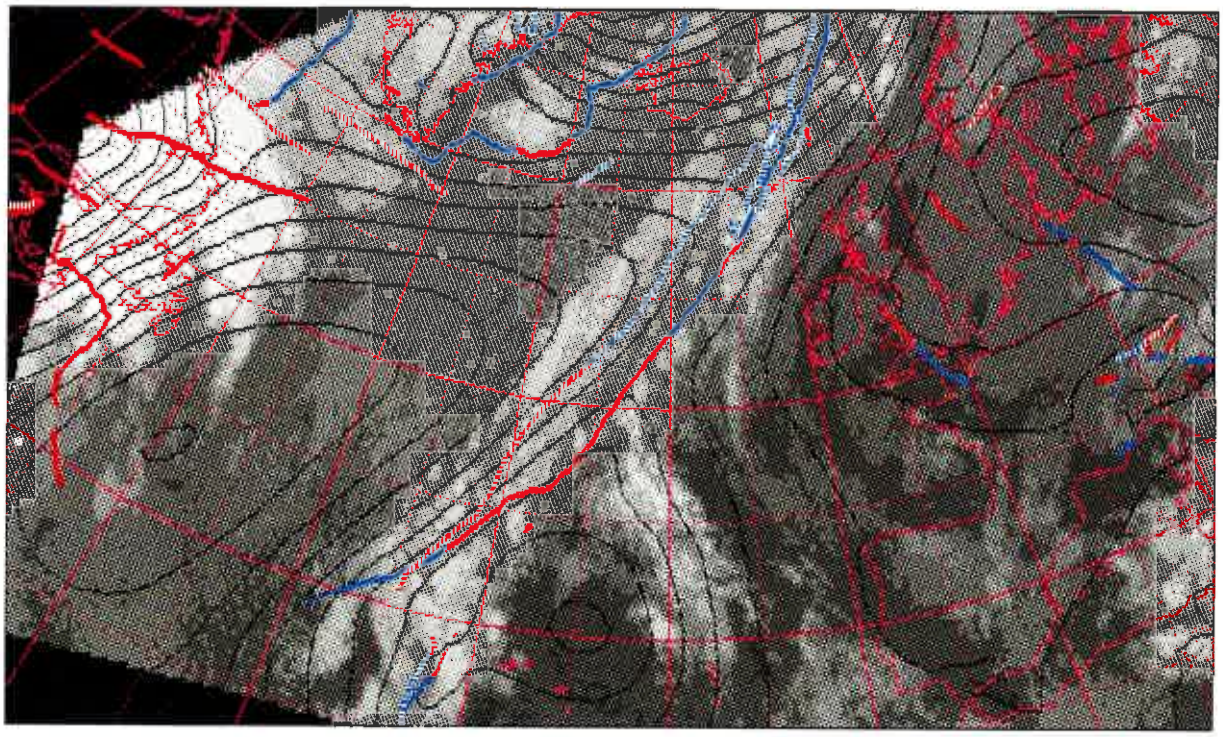
Meteorology of Interest :

Tropopause structure - PV, ozone, Aberystwyth MST radar

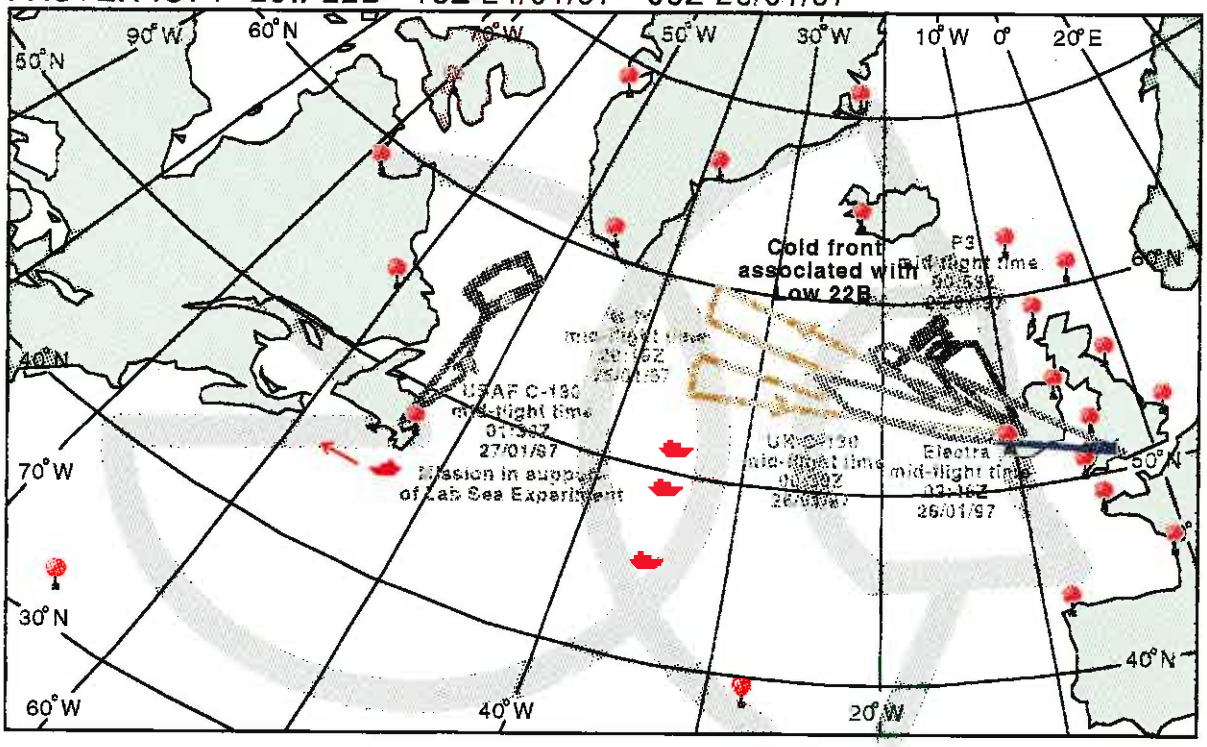
Limitations :

Limited data range especially in MSA

FASTEX IOP 7 Meteosat infrared image 00Z 26/01/97



FASTEX IOP7 Low 22B 18Z 24/01/97 - 06Z 26/01/97



IOP 7 - LOW 22B 24-26 JAN 1997

Flat Frontal Wave translating rapidly NE through Western Half of MSA

Observations :

Aircraft: NUS: G-IV

MSA: UK C-130 (flight A511, 53 LORAN sondes), P3, Electra

Ships: 3

Additional soundings: None

Meteorology of Interest :

Low level flow resembled classical deformation pattern

Case of non development (hopes of upper PV amplification came to nothing)

G-IV flight level data from upper jet entrance

Well defined shallow slope frontal structure

Marked upper level trough (at 30W)

Less precipitation observed than forecast

Signs of excessive model humidity at mid levels in UK LAM

Suggestion that frontal slope was too steep in the UK LAM

Limitations :

Not much of a system (no closed isobars)

IOP 7 - LOW 22B 24-26 JAN 1997

Flat Frontal Wave translating rapidly NE through Western Half of MSA

Observations :

Aircraft: NUS: G-IV

MSA: UK C-130 (flight A511, 53 LORAN sondes), P3, Electra

Ships: 3

Additional soundings: None

Meteorology of Interest :

Low level flow resembled classical deformation pattern

Case of non development (hopes of upper PV amplification came to nothing)

G-IV flight level data from upper jet entrance

Well defined shallow slope frontal structure

Marked upper level trough (at 30W)

Less precipitation observed than forecast

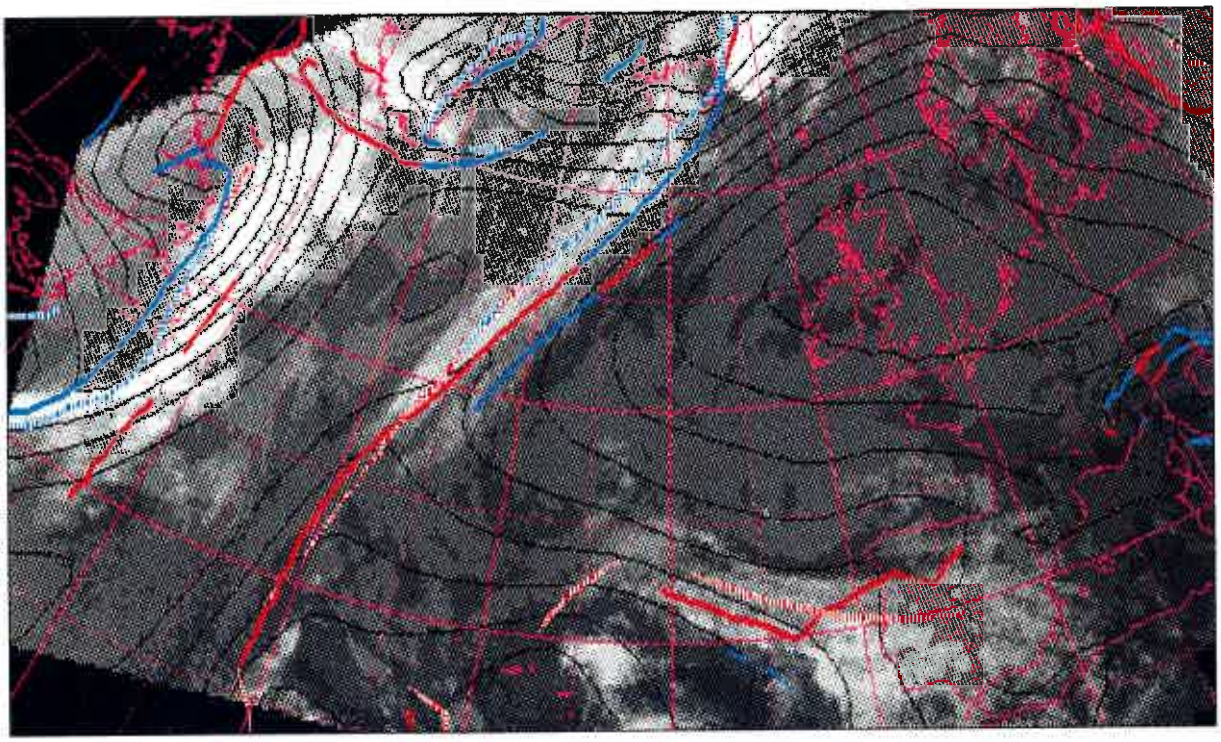
Signs of excessive model humidity at mid levels in UK LAM

Suggestion that frontal slope was too steep in the UK LAM

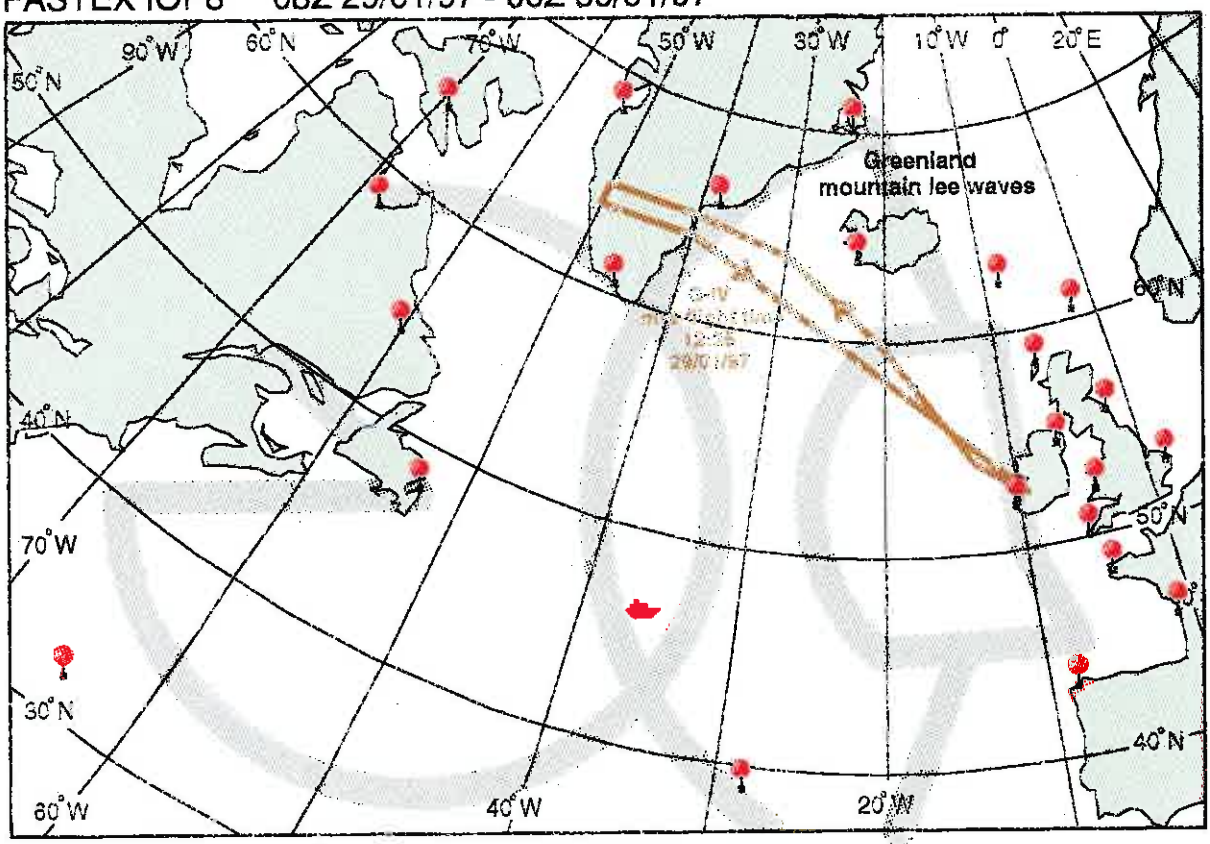
Limitations :

Not much of a system (no closed isobars)

FASTEX IOP 8 Meteosat infrared image 12Z 29/01/97



FASTEX IOP8 08Z 29/01/97 - 00Z 30/01/97



IOP 8 29 JAN 1997

Study of major downslope wave phenomenon to the lee of Greenland

Elongated frontal region to the S of Iceland extending west from developing low to the lee of Greenland

Observations :

Aircraft: Single G-IV flight (targeting using subjective and adjoint methods)

Meteorology of Interest :

Frontal zone to the lee of Greenland

Downslope Wave phenomena

Observed low level jet intensity (45 ms^{-1}) much greater than in model (23ms^{-1})

Frontal Cross Section(s)

Limitations :

Not a FASTEX case

IOP 8 29 JAN 1997

Study of major downslope wave phenomenon to the lee of Greenland

Elongated frontal region to the S of Iceland extending west from developing low to the lee of Greenland

Observations :

Aircraft: Single G-IV flight (targeting using subjective and adjoint methods)

Meteorology of Interest :

Frontal zone to the lee of Greenland

Downslope Wave phenomena

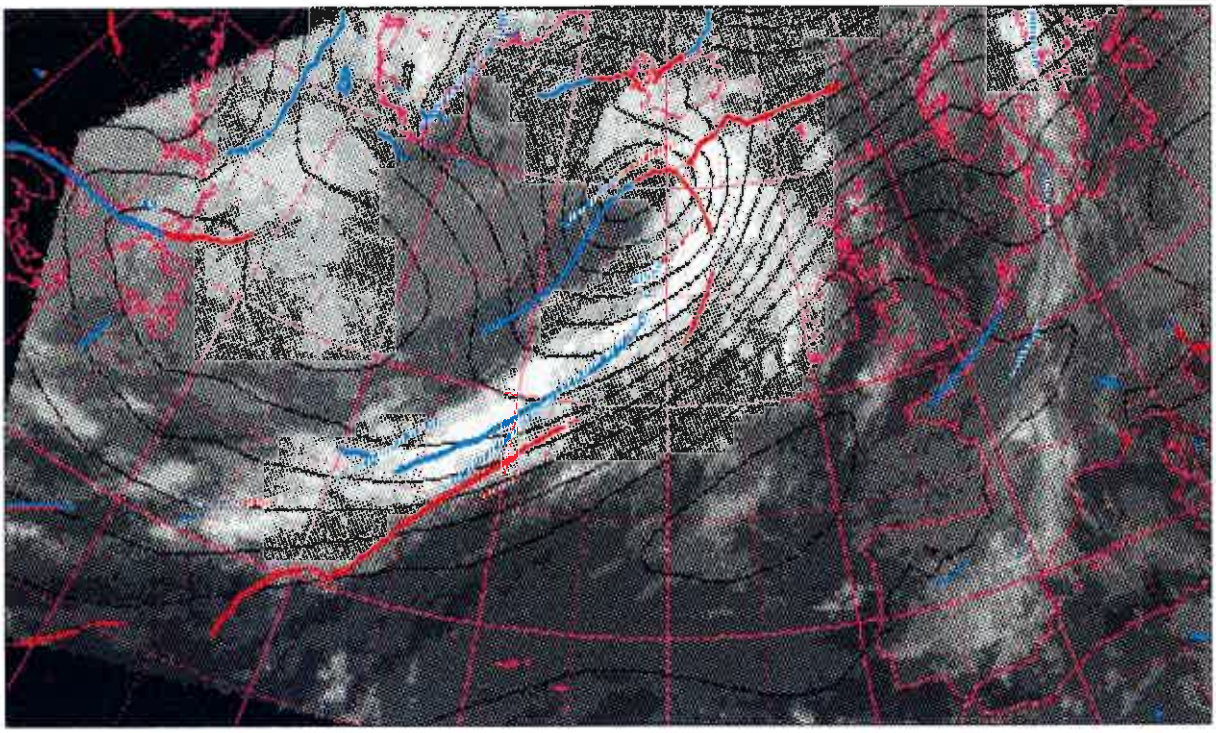
Observed low level jet intensity (45 ms^{-1}) much greater than in model (23ms^{-1})

Frontal Cross Section(s)

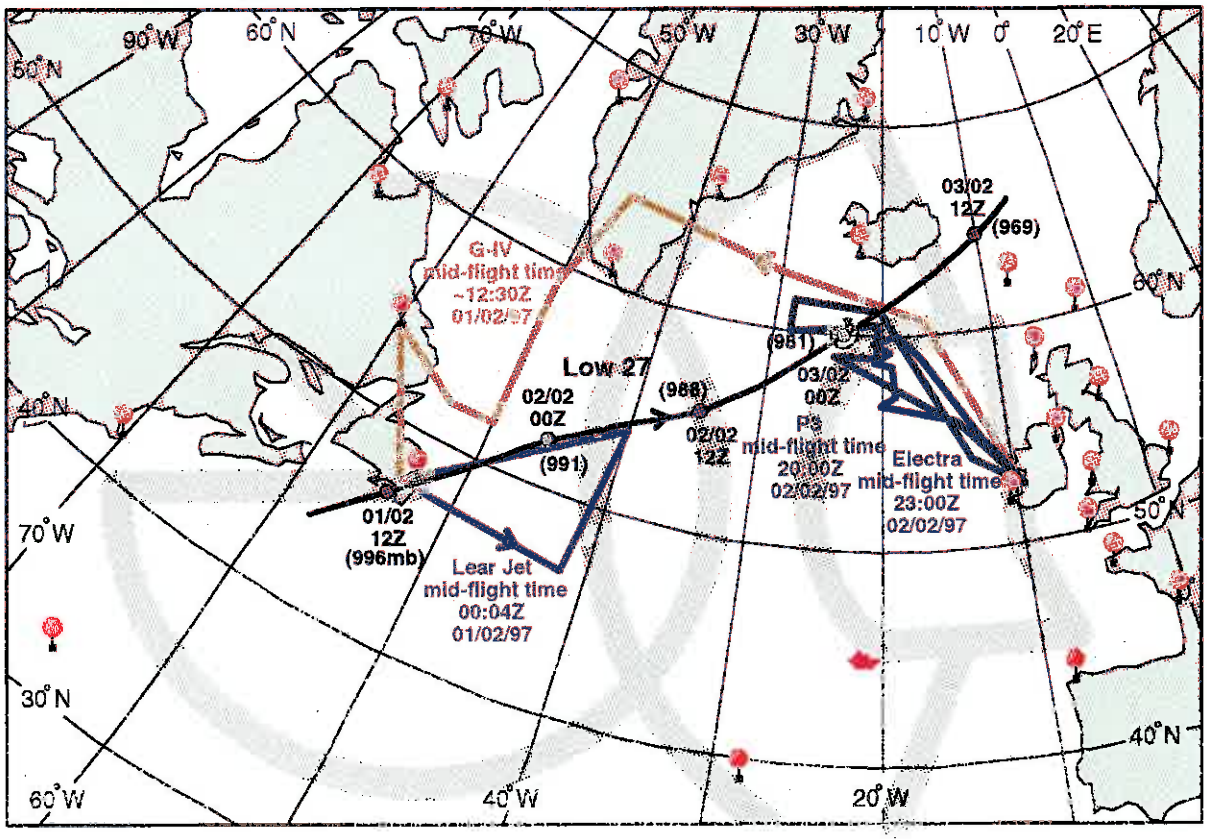
Limitations :

Not a FASTEX case

FASTEX IOP 9 Meteosat infrared image 00Z 03/02/97



FASTEX IOP9 Low 27 06Z 31/01/97 - 15Z 03/02/97



Large, well developed cyclone moved off NE coast of USA. Second major deepening phase occurred to the south of Iceland

Observations :

Aircraft: Upstream: Learjet, G-IV

MSA: P3, Electra

Ships: None

Additional soundings: Upstream North America, Europe coastal

Meteorology of Interest :

Large cyclone with cloud head and dry slot

Already mature in FUS

Significant vertical velocity associated with strong warm front

Strong winds at low levels

Significant PV anomaly at 500mb (1.4 PVU) although PV=2 does not descend below 7.5km

Limitations :

No MSA dropsondes

Incomplete pattern

IOP 9 - LOW 27 31 JAN - 3 FEB 1997

Large, well developed cyclone moved off NE coast of USA. Second major deepening phase occurred to the south of Iceland

Observations :

Aircraft: Upstream: Learjet, G-IV

MSA: P3, Electra

Ships: None

Additional soundings: Upstream US, Europe coastal

Meteorology of Interest :

Large cyclone with cloud head and dry slot

Already mature in FUS

Significant vertical velocity associated with strong warm front

Strong winds at low levels

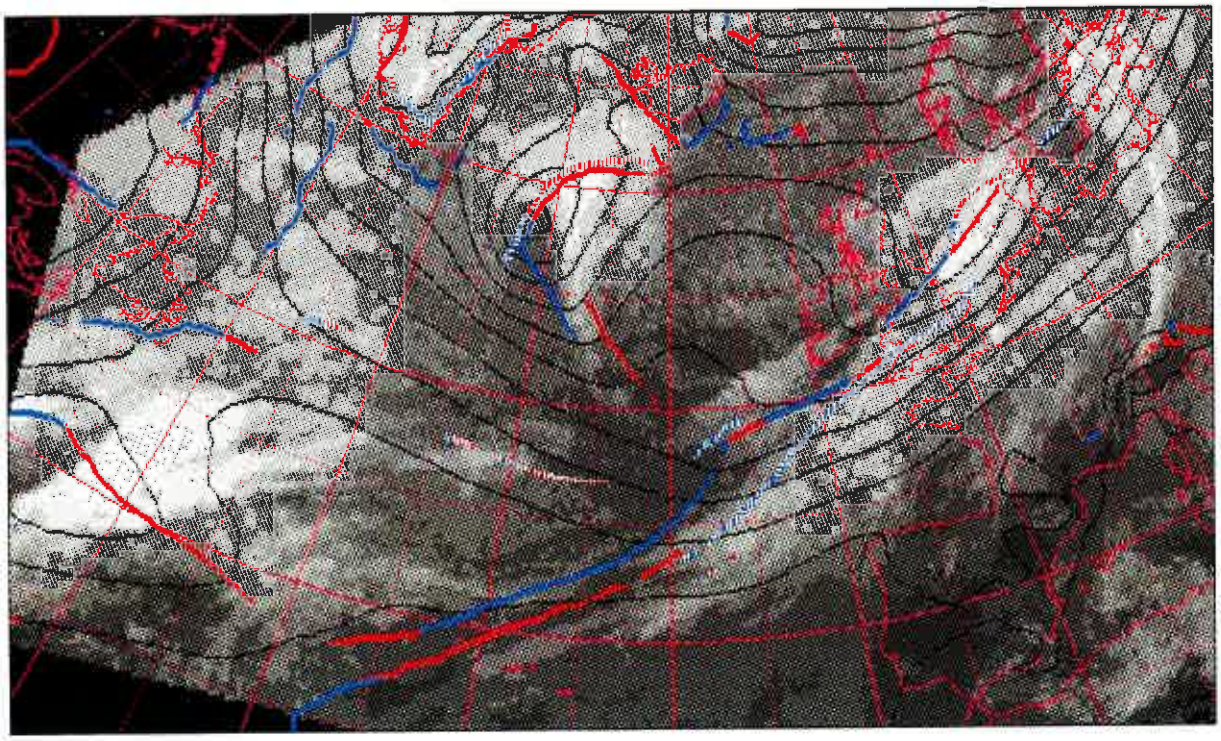
Significant PV anomaly at 500mb (1.4 PVU) although PV=2 does not descend below 7.5km

Limitations :

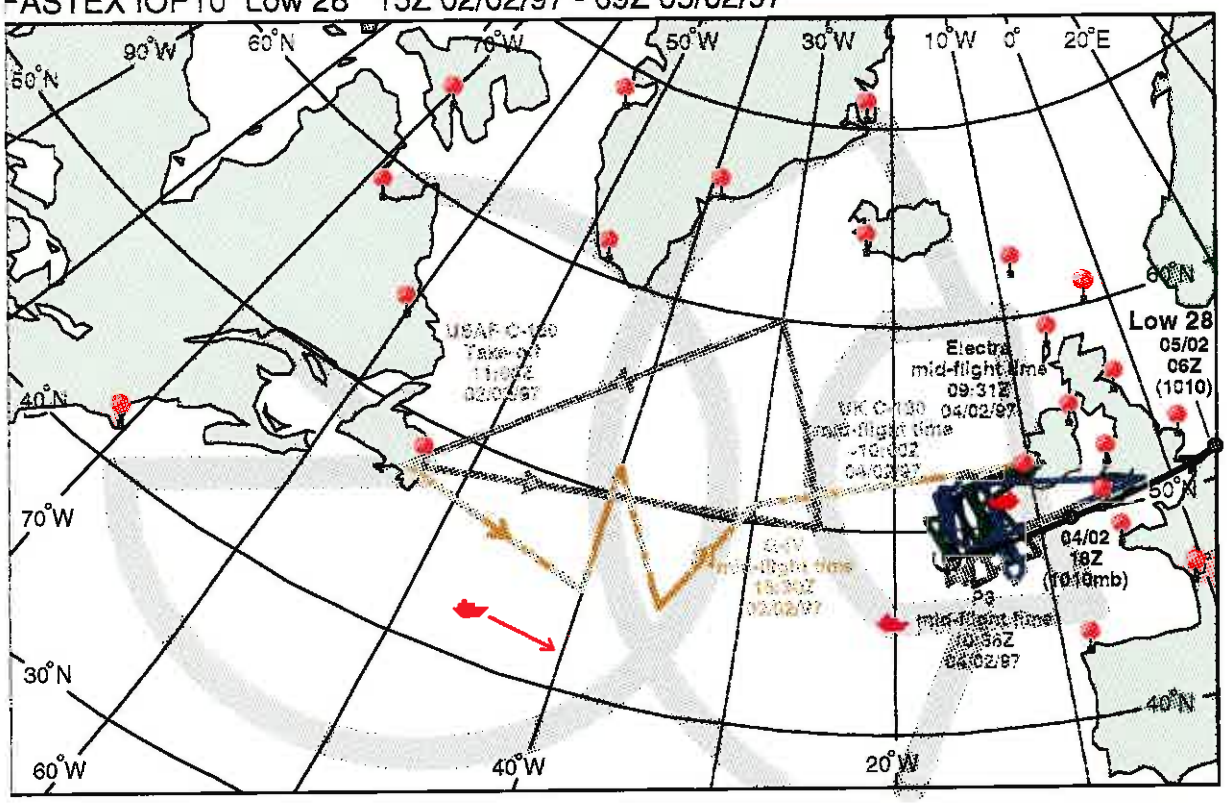
No MSA dropsondes

Incomplete pattern

FASTEX IOP 10 Meteosat infrared image 12Z 04/02/97



FASTEX IOP10 Low 28 15Z 02/02/97 - 09Z 05/02/97



IOP10 - LOW 28 2-5 FEB 1997

Weak frontal wave with strong convection and no closed circulation

Very well observed with a systematic survey and NUS flight

Observations :

Aircraft: Upstream: US-C-130, G-IV (44 sondes)

MSA: UK-C-130 (flight A513, 45 sondes), P3, electra

Ships: 2 (including one in the MSA area)

Additional soundings: Upstream North America, Europe coastal

Meteorology of Interest :

Weak frontal wave, poorly forecast to develop more strongly; large differences in forecasts

Cloud head, dry intrusion and associated convection

The tropopause region associated with this system can be followed all the way across the Atlantic

Low tropopause well observed during the lifecycle

Limitations :

First UK C-130 GPS dropsonde flight, some data problems

IOP10 - LOW 28 2-5 FEB 1997

Weak frontal wave with strong convection and no closed circulation

Very well observed with a systematic survey and NUS flight

Observations :

Aircraft: Upstream: US-C-130, G-IV (44 sondes)

MSA: UK-C-130 (flight A513, 45 sondes), P3, electra

Ships: 2 (including one in the MSA area)

Additional soundings: Upstream US, Europe coastal

Meteorology of Interest :

Weak frontal wave, poorly forecast to develop more strongly; large differences in forecasts

Cloud head, dry intrusion and associated convection

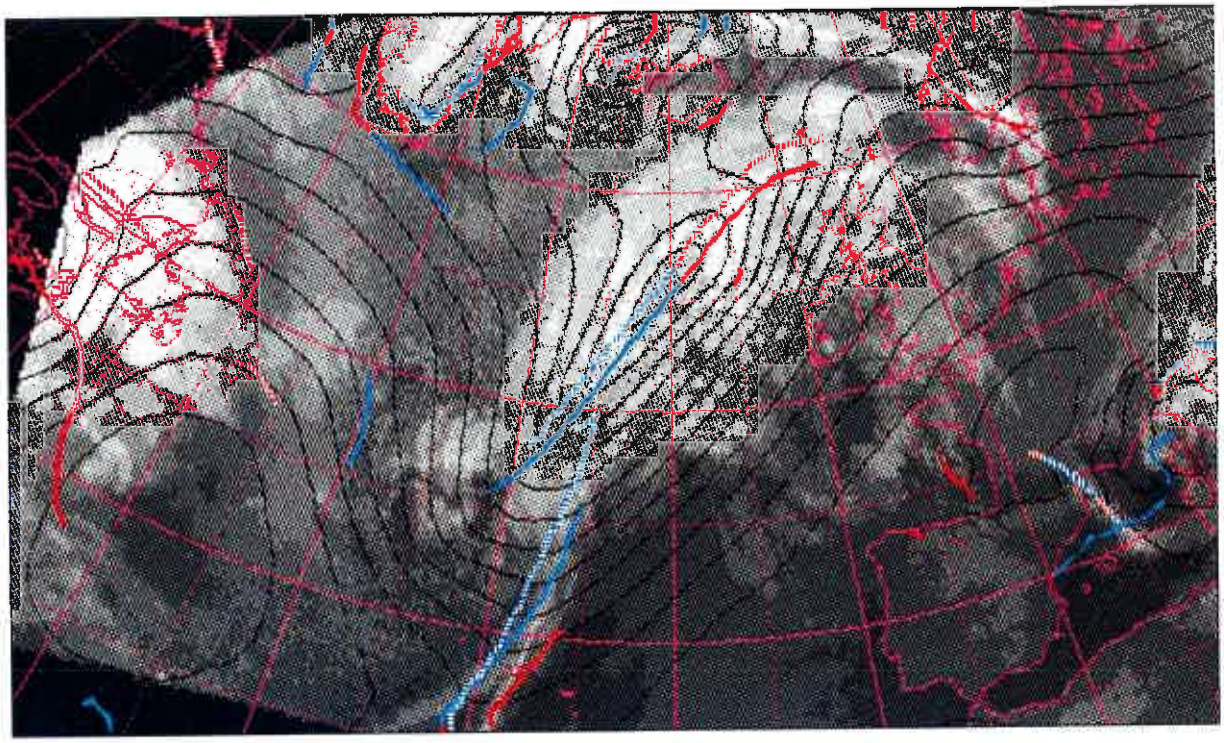
The tropopause region associated with this system can be followed all the way across the Atlantic

Low tropopause well observed during the lifecycle

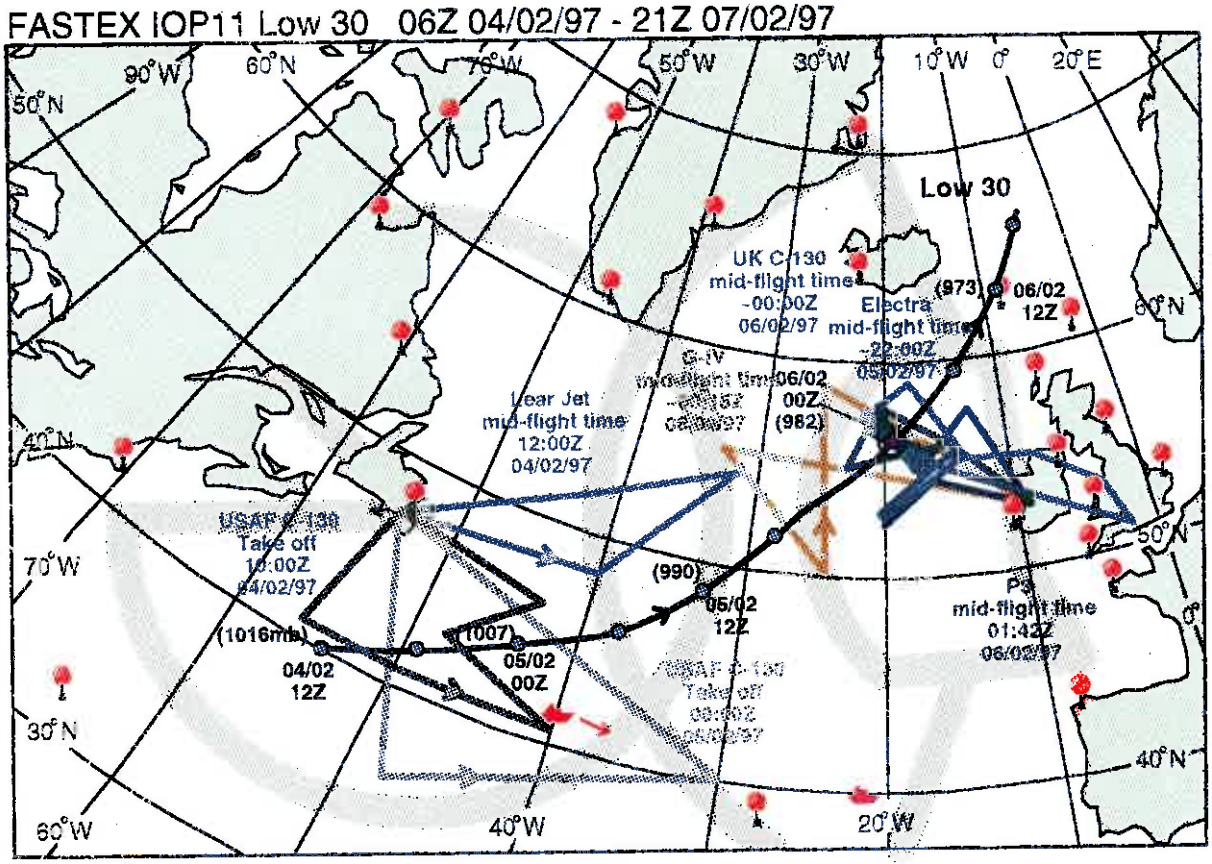
Limitations :

First UK C-130 GPS dropsonde flight, some data problems

FASTEX IOP 11 Meteosat infrared image 00Z 06/02/97



FASTEX IOP11 Low 30 06Z 04/02/97 - 21Z 07/02/97



IOP 11 - LOW 30 4-7 FEB 1997

Primary cyclone forming over the east of North America and deepening while crossing the Atlantic (strong ascent in the cloud head and ahead of the warm front)

Observations :

Aircraft: FUS: Lear Jet and US-C-130 investigated the low and its trailing cold front in the early stage (objective targets)

NUS: US-C-130 (and GOES Rapid scans) observed the developing phase

MSA: 4 aircraft survey studied the mature phase. UK-C-130 (flight A514, 90 sondes) & Electra observed the warm front. UK-C-130 & P3 investigated the cyclone centre. G-IV investigated the region south of the cyclone centre

Ships: 1 ship observed the developing phase - others moving towards 35W

Additional soundings: Upstream North America and 3-hourly ozone soundings from Valentia and
Aberystwyth

Meteorology of Interest :

Warm front - mesoscale structure highlighted in the dropsondes

Only small forecast errors. The forecast of the low centre location and the intensity of the system was quite accurate, with position error around 150 km (36 hour forecast).

IOP 11 - LOW 30 4-7 FEB 1997

Primary cyclone forming over the east of North America and deepening while crossing the Atlantic (strong ascent in the cloud head and ahead of the warm front)

Observations :

Aircraft: FUS: Lear Jet and US-C-130 investigated the low and its trailing cold front in the early stage (objective targets)

NUS: US-C-130 (and GOES Rapid scans) observed the developing phase

MSA: 4 aircraft survey studied the mature phase. UK-C-130 (flight A514, 90 sondes) & Electra observed the warm front. UK-C-130 & P3 investigated the cyclone centre. G-IV investigated the region south of the cyclone centre

Ships: 1 ship observed the developing phase - others moving towards 35W

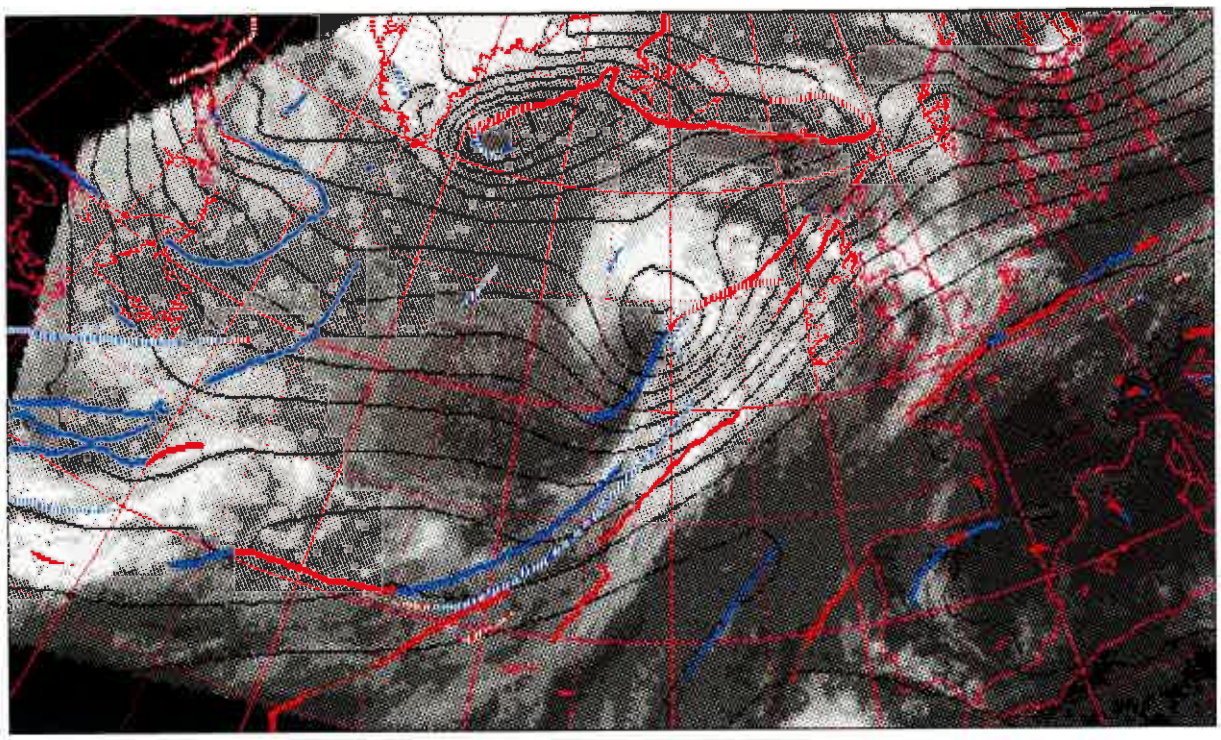
Additional soundings: Upstream US and 3-hourly ozone soundings from Valentia and Aberystwyth

Meteorology of Interest :

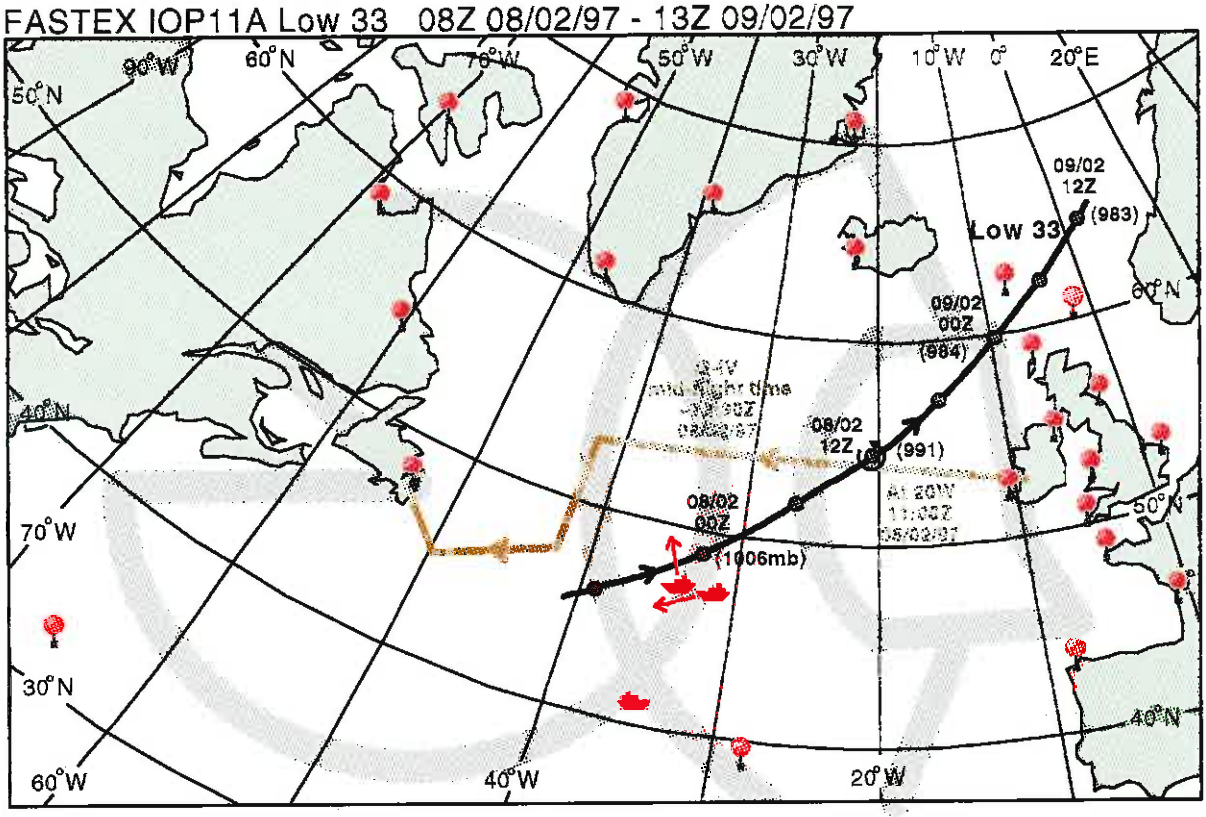
Warm front - mesoscale structure highlighted in the dropsondes

Only small forecast errors. The forecast of the low centre location and the intensity of the system was quite accurate, with position error around 150 km (36 hour forecast).

FASTEX IOP 11A Meteosat infrared image 12Z 08/02/97



FASTEX IOP11A Low 33 08Z 08/02/97 - 13Z 09/02/97



IOP11A - LOW 33 8-9 FEB 1997

Developing cold frontal wave - classic example of a FASTEX cyclone

Observations :

Aircraft: Upstream: None

MSA: G-IV (10 sondes)

Ships: 2 relevant and 1 other further south (for IOP 12)

Additional soundings: Upstream North America

Meteorology of Interest :

Single G-IV cross-section through low 33

Poor LAM forecasts

Good history of water vapour dry slot seen from Meteosat imagery

Improvement in UKMO LAM and the French ARPEGE forecasts with G-IV data

Limitations :

No flight by UK C-130, P3 or Electra

IOP11A - LOW 33 8-9 FEB 1997

Developing cold frontal wave - classic example of a FASTEX cyclone

Observations :

Aircraft: Upstream: None

MSA: G-IV (10 sondes)

Ships: 2 relevant and 1 other further south (for IOP 12)

Additional soundings: Upstream US

Meteorology of Interest :

Single G-IV cross-section through low 33

Poor LAM forecasts

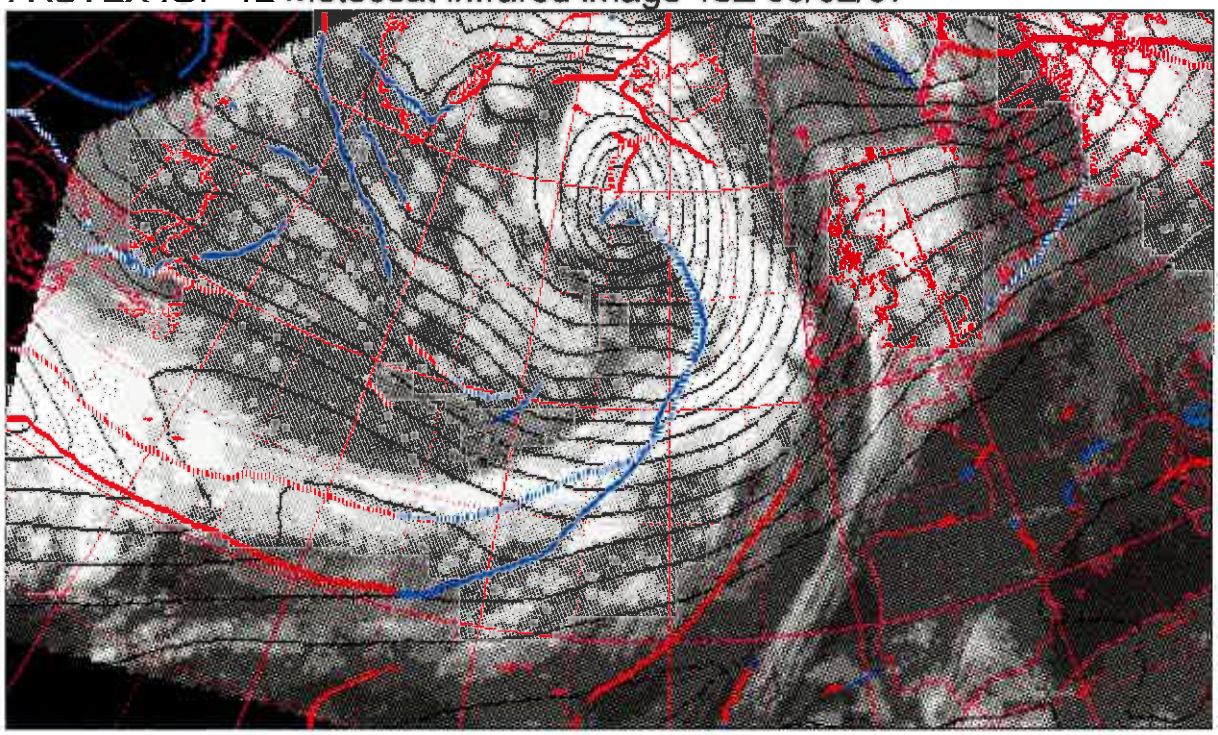
Good history of water vapour dry slot seen from Meteosat imagery

Improvement in UKMO LAM and the French ARPEGE forecasts with G-IV data

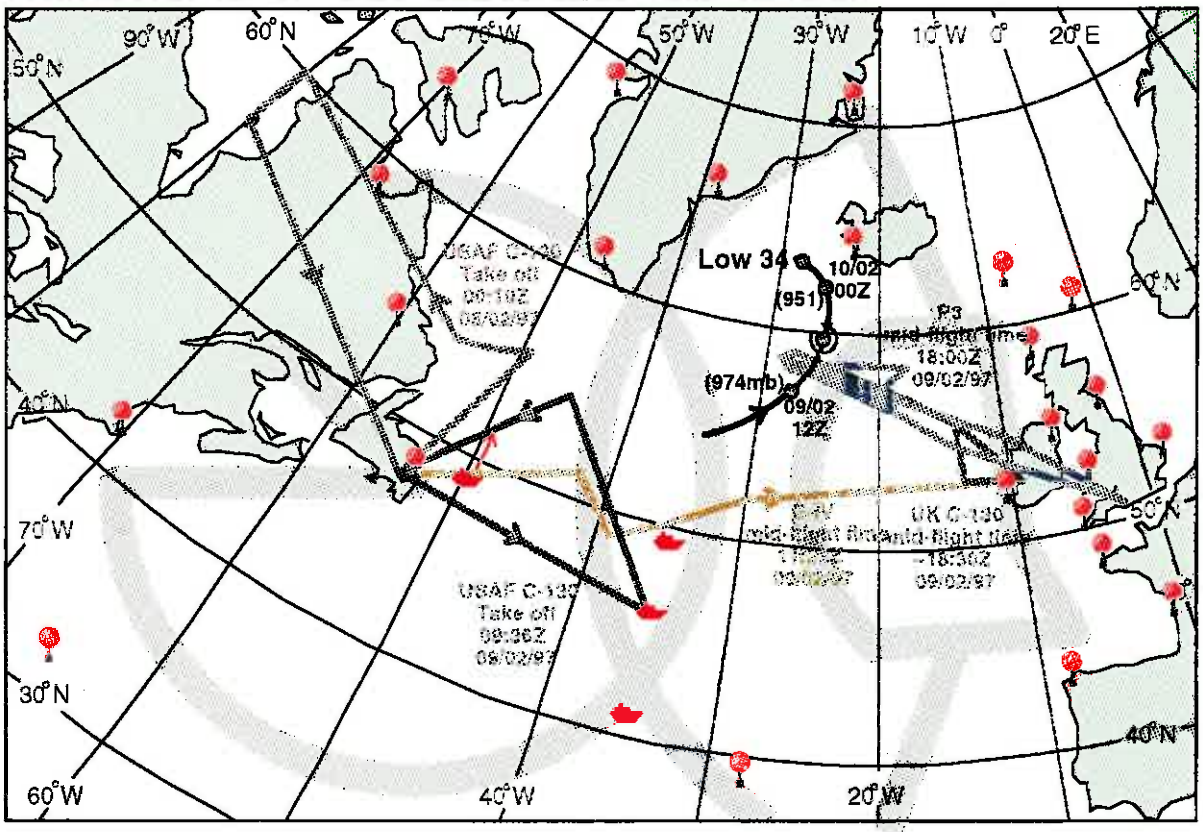
Limitations :

No flight by UK C-130, P3 or Electra

FASTEX IOP 12 Meteosat infrared image 18Z 09/02/97



FASTEX IOP12 Low 34A 06Z 08/02/97 - 00Z 10/02/97



IOP12 - LOW 34A 8-9 FEB 1997

Investigation of explosive cyclogenesis

Test for different targeting techniques in the FUS area (bred modes, singular vectors, sensitivity patterns)

Cloud head, dry slot and cold front observed with dropsondes

Observations :

Aircraft: Upstream: US-C-130 (2 flights), G-IV

MSA: UK-C-130 (flight A515, 68 sondes), P3

Ships: 3 + 1 moving towards Labrador Sea

Additional soundings: Upstream North America, Europe coastal

Meteorology of Interest :

Massive divergence in forecasts between different models

Poor forecast

Stratospheric air observed plunging down into the dry slot

Organised line of thunderstorms (several hundred kms long).

Limitations :

Dropsonde data: good for verification of the model, not for cross-sections

System tracking too far from MSA

IOP12 - LOW 34A 8-9 FEB 1997

Investigation of explosive cyclogenesis

Test for different targeting techniques in the FUS area (bred modes, singular vectors, sensitivity patterns)

Cloud head, dry slot and cold front observed with dropsondes

Observations :

Aircraft: Upstream: US-C-130 (2 flights), G-IV

MSA: UK-C-130 (flight A515, 68 sondes), P3

Ships: 3 + 1 moving towards Labrador Sea

Additional soundings: Upstream US, Europe coastal

Meteorology of Interest :

Massive divergence in forecasts between different models

Poor forecast

Stratospheric air observed plunging down into the dry slot

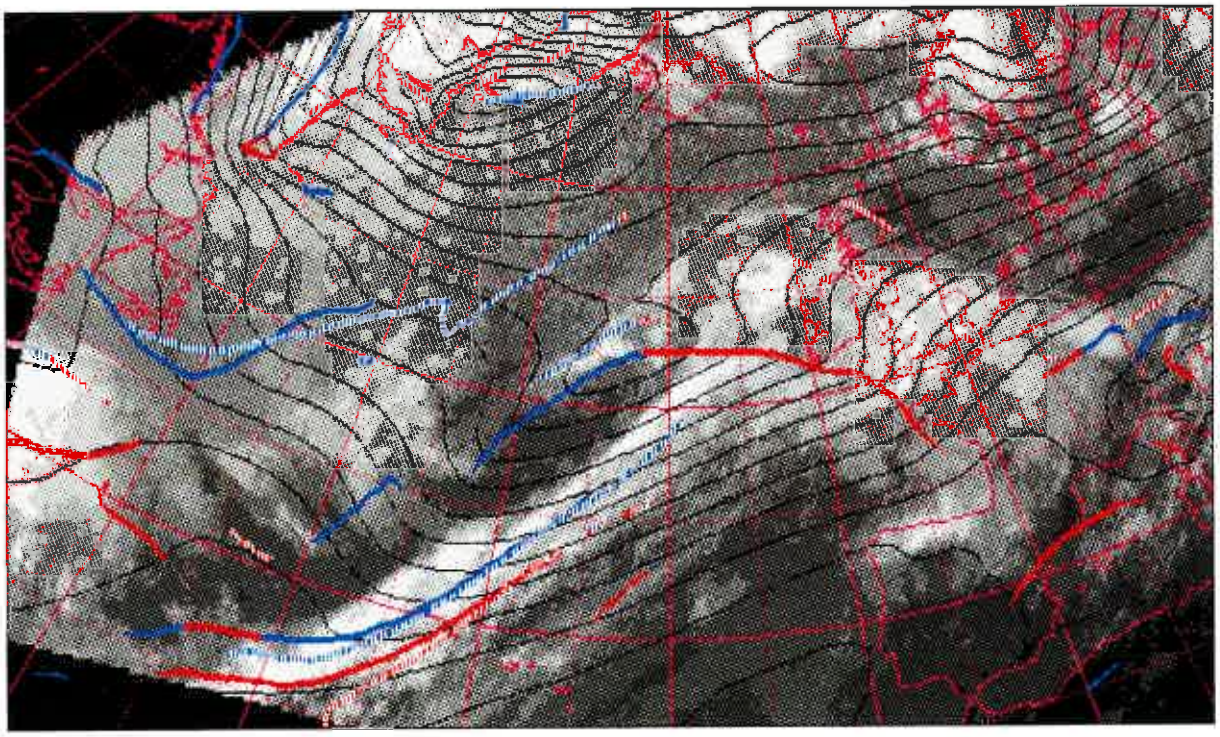
Organised line of thunderstorms (several hundred kms long).

Limitations :

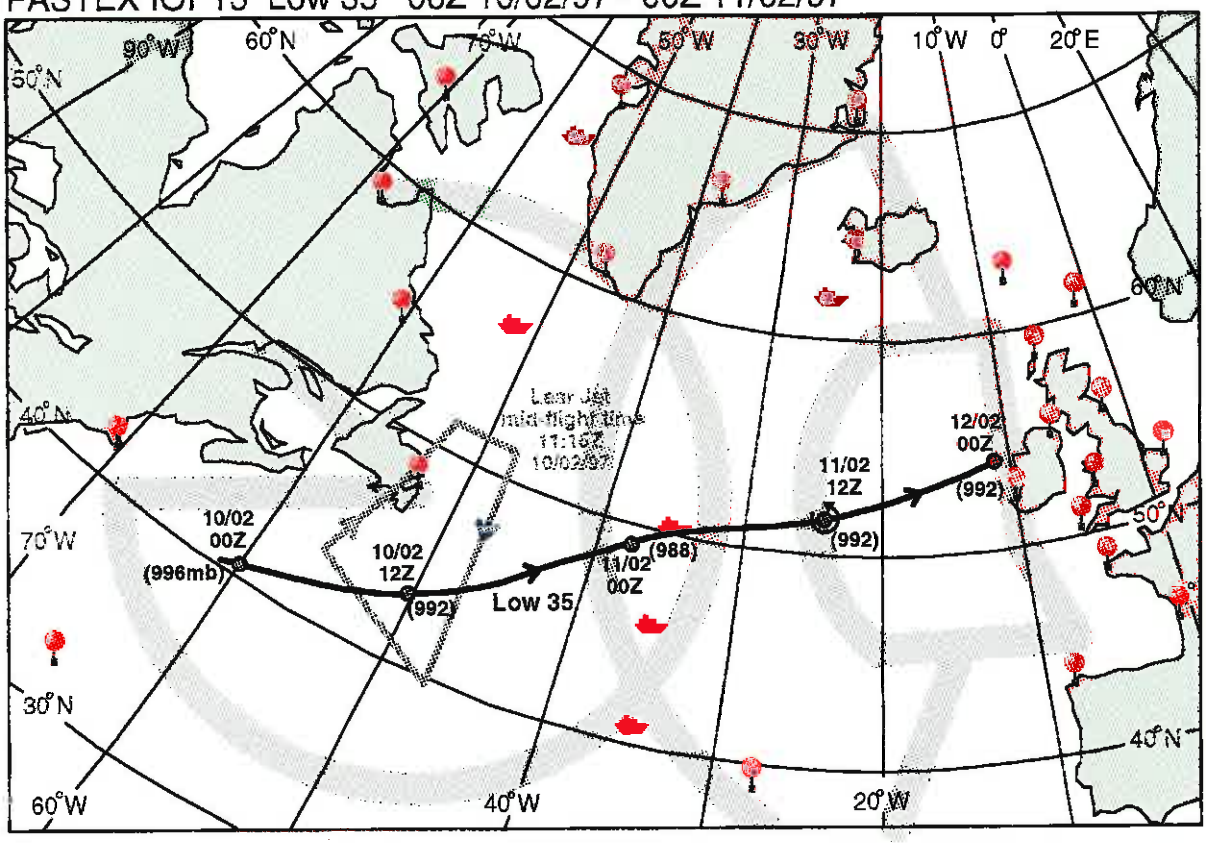
Dropsonde data: good for verification of the model, not for cross-sections

System tracking too far from MSA

FASTEX IOP 13 Meteosat infrared image 12Z 11/02/97



FASTEX IOP13 Low 35 06Z 10/02/97 - 00Z 11/02/97



IOP 13 - LOW 35 10-11 FEB 1997

Decaying mature wave heading towards Northern Britain

Observations :

Aircraft: Upstream: Lear

Ships: 3 (1.5 hourly) + Labrador Sea experiment

Additional soundings: no, but some of the IOP 12 or IOP 14 soundings may be relevant

Meteorology of Interest :

The 36 hour forecast was accurate in location but wrong in intensity, with a 8 mb error (the forecast was for a deeper system).

Limitations :

No MSA flights

IOP 13 - LOW 35 10-11 FEB 1997

Decaying mature wave heading towards Northern Britain

Observations :

Aircraft: Upstream: Lear

Ships: 3 (1.5 hourly) + Labrador Sea experiment

Additional soundings: no, but some of the IOP 12 or IOP 14 soundings may be relevant

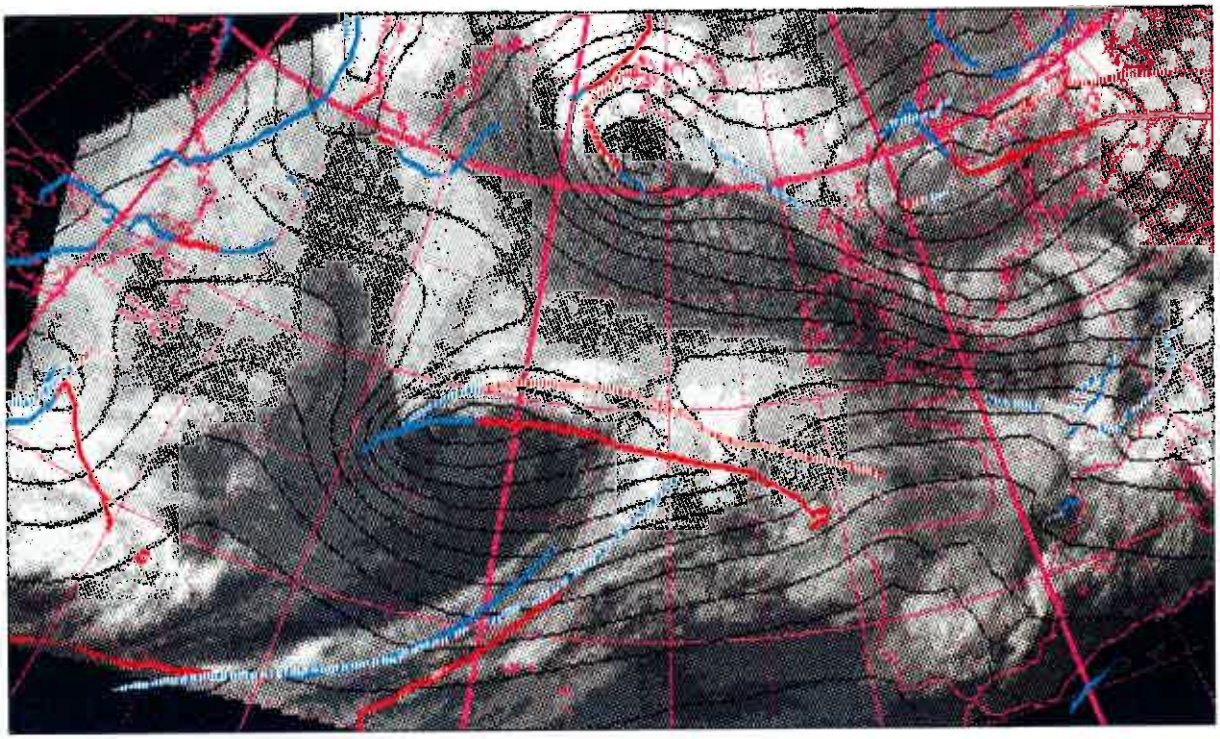
Meteorology of Interest :

The 36 hour forecast was accurate in location but wrong in intensity, with a 8 mb error (the forecast was for a deeper system).

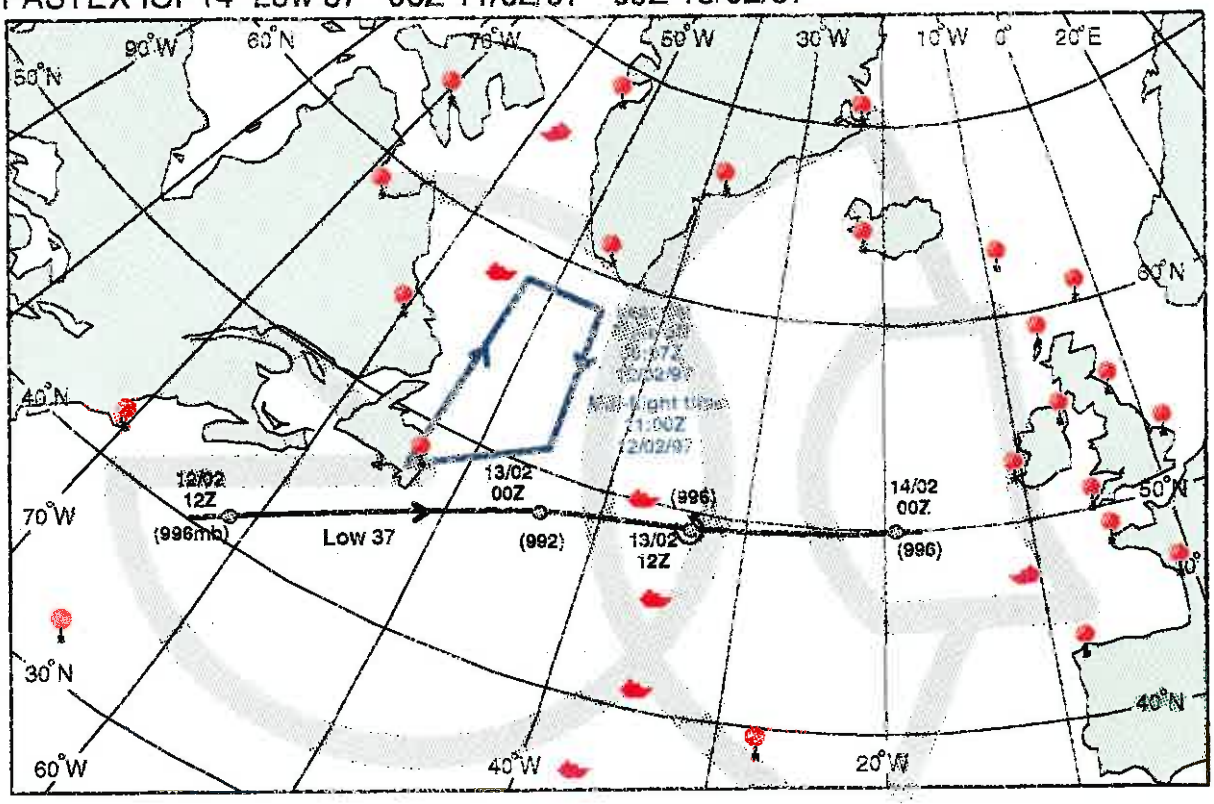
Limitations :

No MSA flights

FASTEX IOP 14 Meteosat infrared image 12Z 13/02/97



FASTEX IOP14 Low 37 06Z 11/02/97 - 09Z 13/02/97



IOP 14 - LOW 37 11- 13 FEB 1997

Slowly weakening, elongated low

Observations :

Aircraft: Upstream: Lear, G-IV

Ships: 3 + Labrador Sea experiment

Additional soundings: US coastal

Meteorology of Interest :

Upper trough linked to low sampled by Lear jet

System deepened initially, but then filled as it approached the MSA

Limitations :

No MSA flights

IOP 14 - LOW 37 11- 13 FEB 1997

Slowly weakening, elongated low

Observations :

Aircraft: Upstream: Lear, G-IV

Ships: 3 + Labrador Sea experiment

Additional soundings: US coastal

Meteorology of Interest :

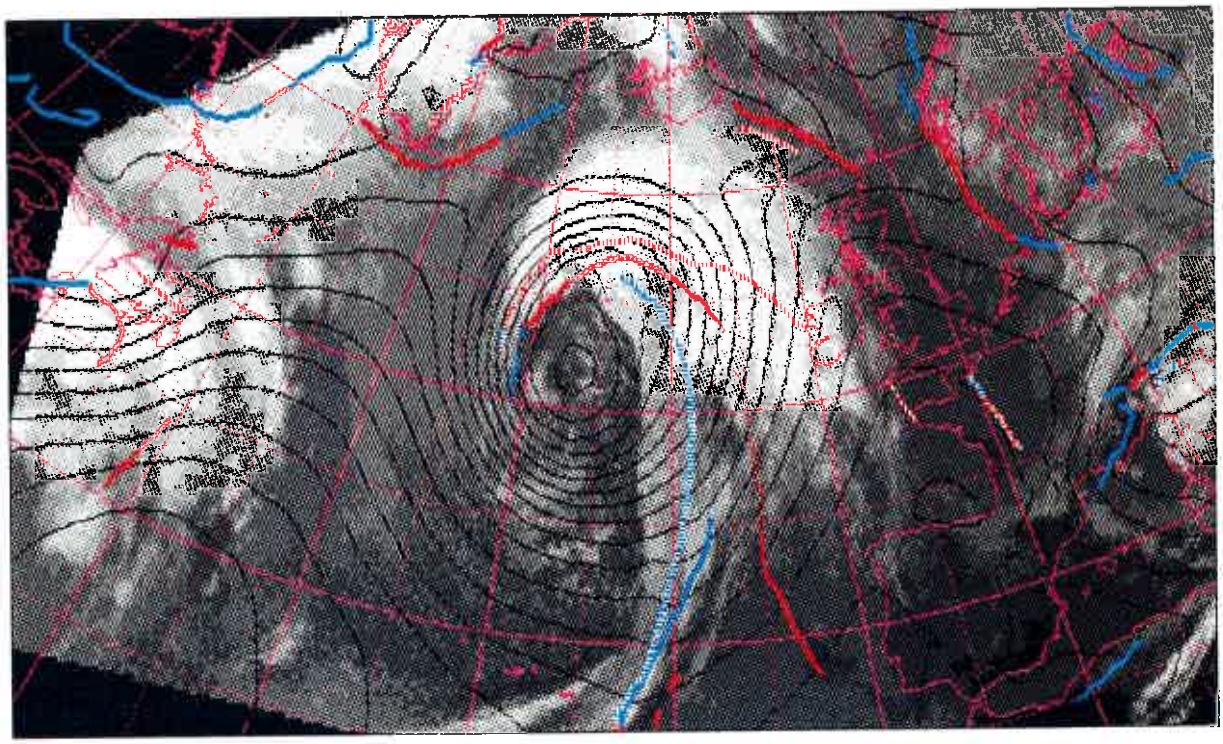
Upper trough linked to low sampled by Lear jet

System deepened initially, but then filled as it approached the MSA

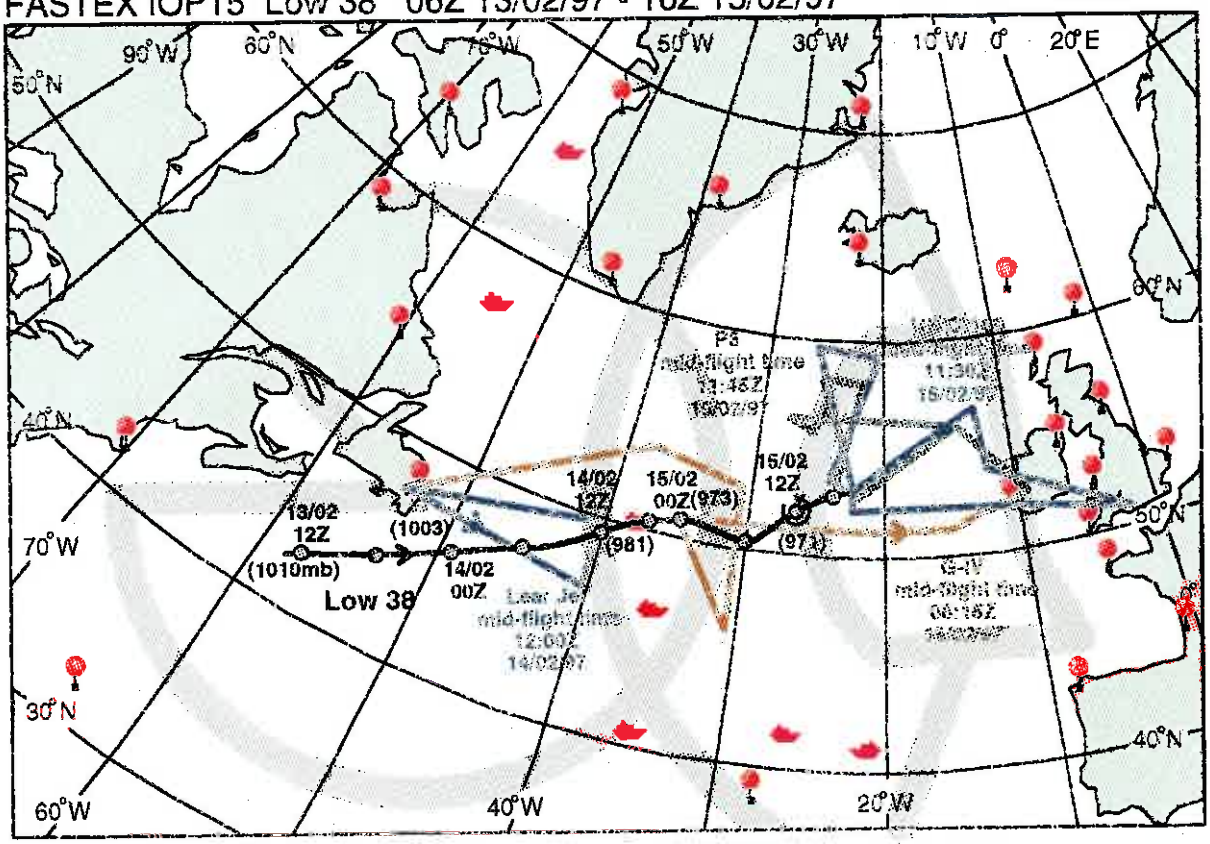
Limitations :

No MSA flights

FASTEX IOP 15 Meteosat infrared image 12Z 15/02/97



FASTEX IOP15 Low 38 06Z 13/02/97 - 16Z 15/02/97



IOP15 - LOW 38 13-15 FEB 1997

Excellent 3-arc systematic survey of mature cyclone warm occlusion in the MSA

Cloud Head observed with the P-3 Doppler radar

G-IV dropsonde and stratospheric ozone measurements in cyclone centre

Observations :

Aircraft: Upstream: Learjet, G-IV (30 sondes)

MSA: P3, UK C-130 (flight A516, 47 sondes)

Ships: 3 + 1 Labrador Sea experiment

Additional soundings: Upstream North America, Europe coastal

Meteorology of Interest :

Well-forecast and well-observed evolution with interesting mesoscale structure

Good systematic survey for process studies

Successive measurements along flow structure showing very consistent patterns and feature identification

Occlusions are little observed

Limitations :

Too mature - not a FASTEX-type cyclone!

IOP15 - LOW 38 13-15 FEB 1997

Excellent 3-arc systematic survey of mature cyclone warm occlusion in the MSA

Cloud Head observed with the P-3 Doppler radar

G-IV dropsonde and stratospheric ozone measurements in cyclone centre

Observations :

Aircraft: Upstream: Learjet, G-IV (30 sondes)

MSA: P3, UK C-130 (flight A516, 47 sondes)

Ships: 3 + 1 Labrador Sea experiment

Additional soundings: Upstream US, Europe coastal

Meteorology of Interest :

Well-forecast and well-observed evolution with interesting mesoscale structure

Good systematic survey for process studies

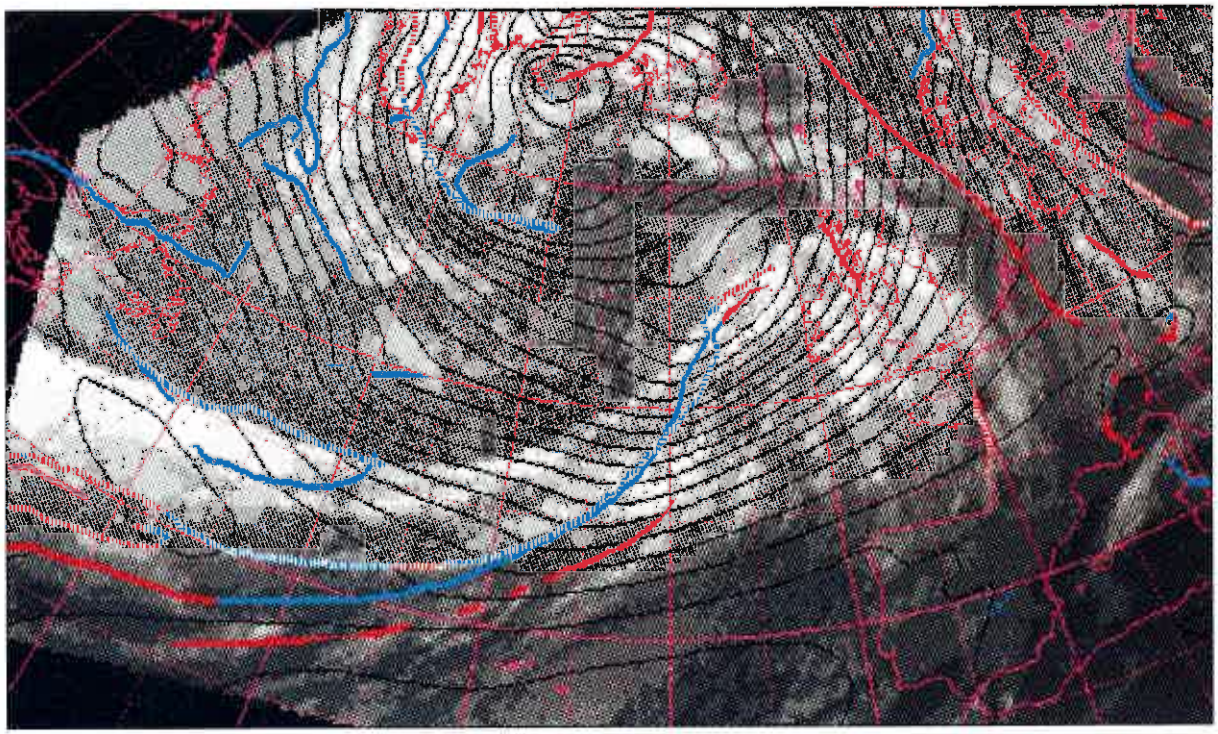
Successive measurements along flow structure showing very consistent patterns and feature identification

Occlusions are little observed

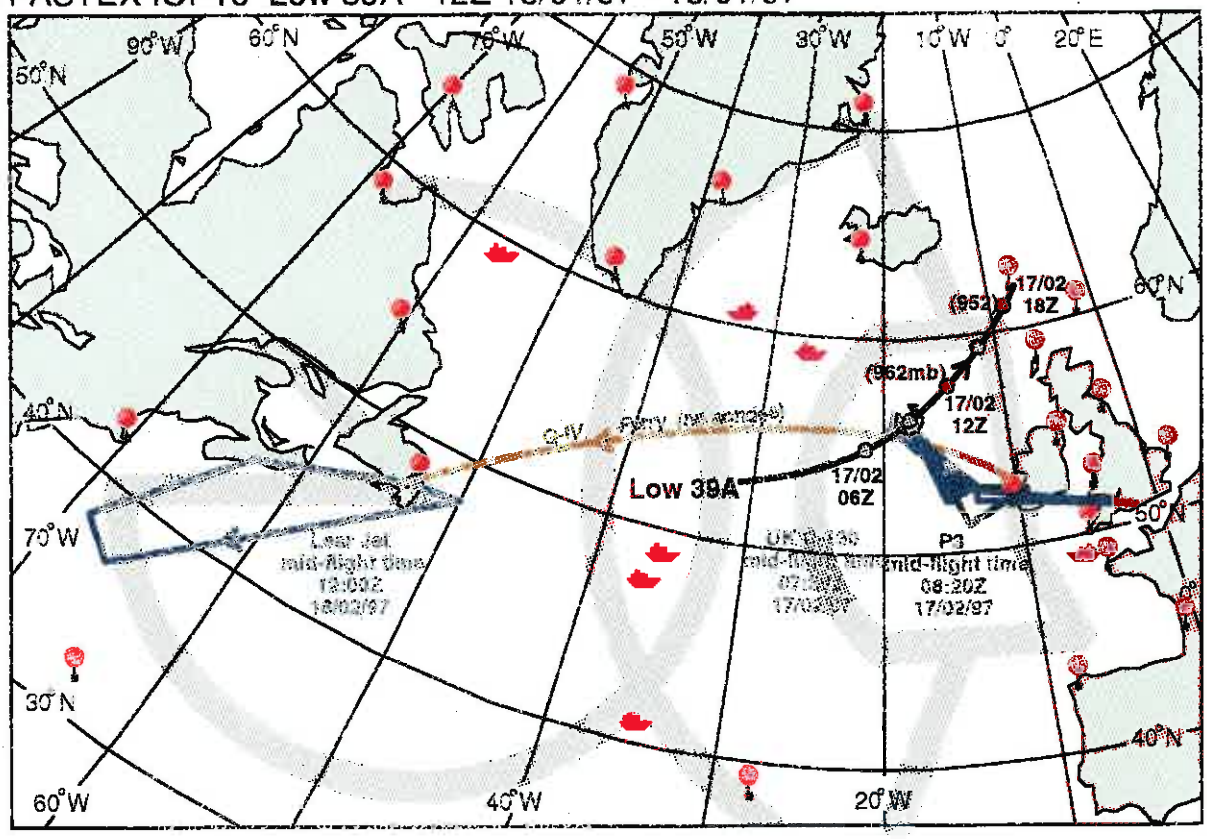
Limitations :

Too mature - not a FASTEX-type cyclone!

FASTEX IOP 16 Meteosat infrared image 09Z 17/02/97



FASTEX IOP16 Low 39A 12Z 15/01/97 - 18/01/97



IOP16 - LOW 39A 15-18 FEB 1997

Fast moving, rapidly deepening, secondary wave, FASTEX type cyclone with emerging cloud head and distinct dry intrusion moves through MSA

Observations :

Aircraft: FUS: Learjet (Objective),

MSA: G-IV (flight level data only), UK C-130 (flight A517, 62 sondes), P3

Ships: 3 + Labrador Sea experiment

Additional soundings: Upstream North America, Europe coastal

Meteorology of Interest :

Rapidly deepening but only because moving close to parent low (throughout MSA period, no 1mb closed isobars)

Fast moving ($29ms^{-1}$)

Pronounced dry intrusion in MSA which may have been captured in FUS by Lear Jet flight

Emerging cloud head in MSA period

Primary cold front changes from rearward to forward sloping in MSA

Very strong 900mb winds ($40ms^{-1}$)

Low level vorticity strip at early stages

Negative 300mb PV anomaly covered by MSA flight tracks

UKMO model 24, 48 and 72 hour forecasts good

IOP16 - LOW 39A 15-18 FEB 1997

Fast moving, rapidly deepening, secondary wave, FASTEX type cyclone with emerging cloud head and distinct dry intrusion moves through MSA

Observations :

Aircraft: FUS: Learjet (Objective),

MSA: G-IV (flight level data only), UK C-130 (flight A517, 62 sondes), P3

Ships: 3 + Labrador Sea experiment

Additional soundings: Upstream US, Europe coastal

Meteorology of Interest :

Rapidly deepening but only because moving close to parent low (throughout MSA period, no 1mb closed isobars)

Fast moving (29ms^{-1})

Pronounced dry intrusion in MSA which may have been captured in FUS by Lear Jet flight

Emerging cloud head in MSA period

Primary cold front changes from rearward to forward sloping in MSA

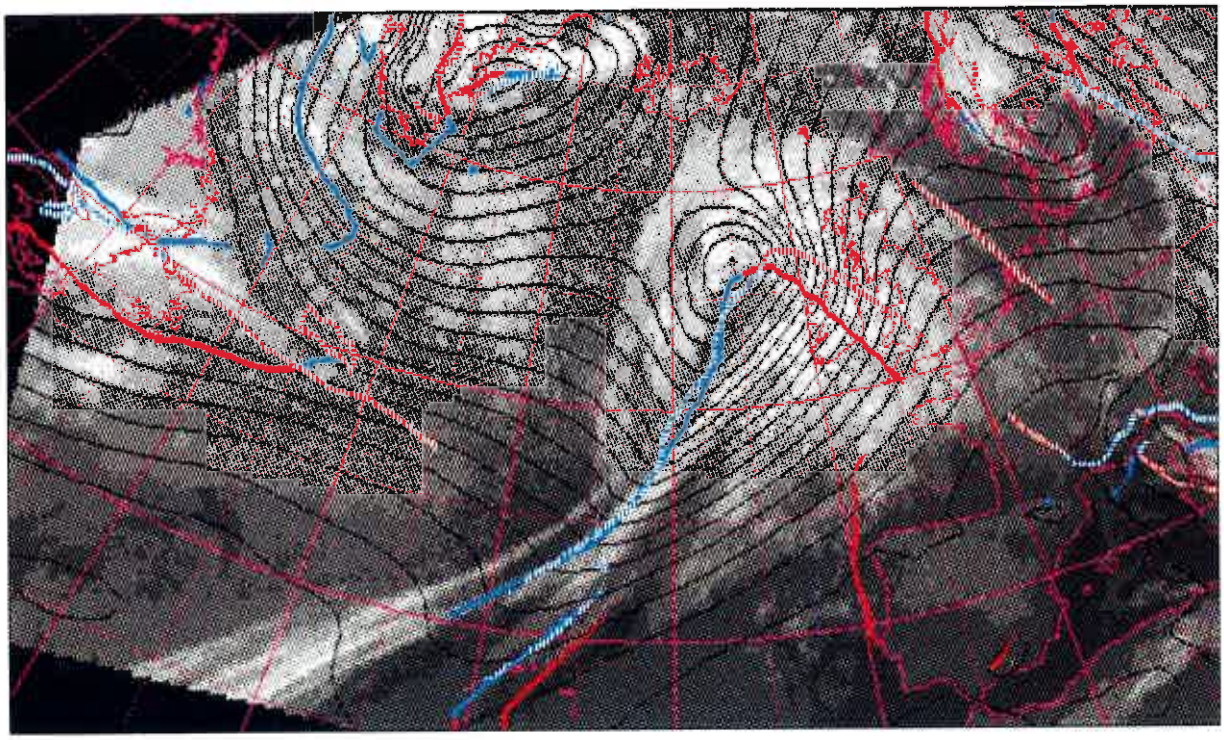
Very strong 900mb winds (40ms^{-1})

Low level vorticity strip at early stages

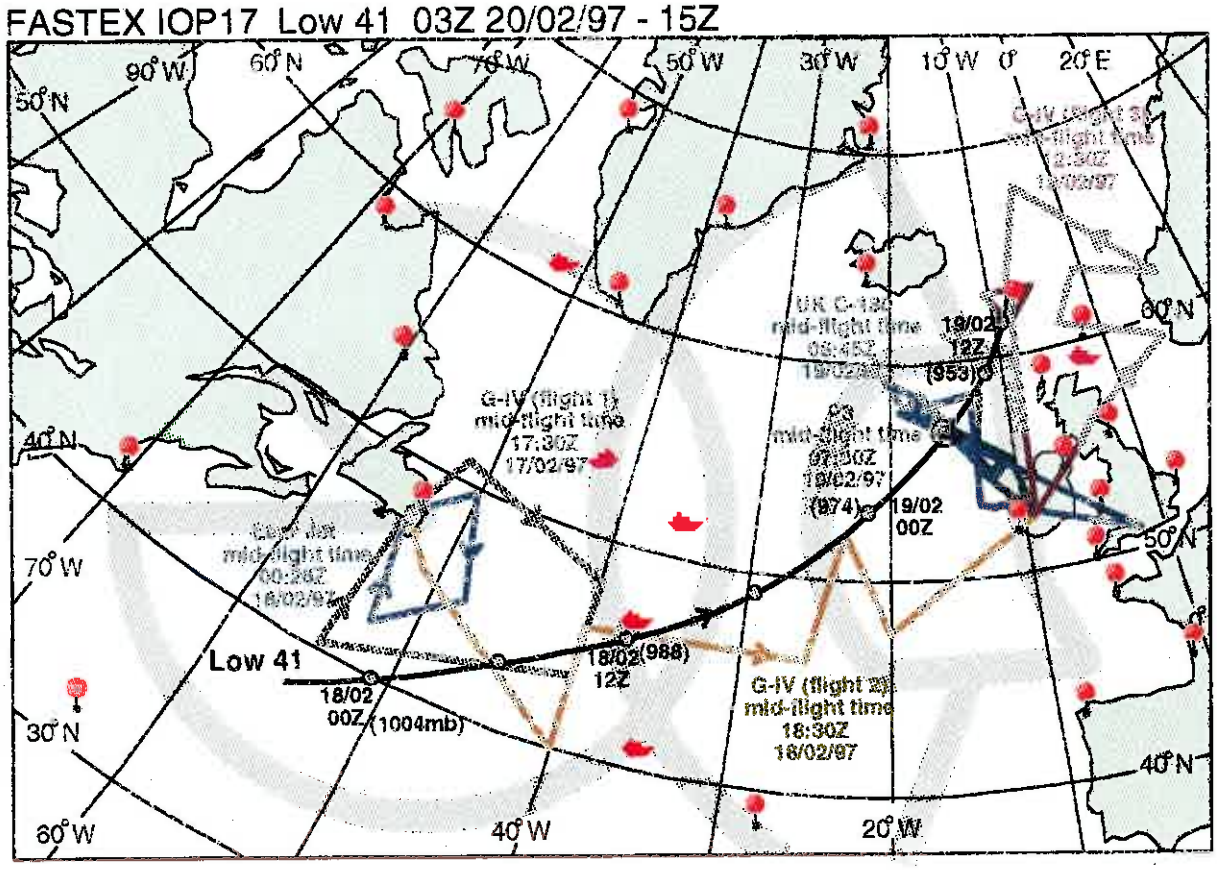
Negative 300mb PV anomaly covered by MSA flight tracks

UKMO model 24, 48 and 72 hour forecasts good

FASTEX IOP 17 Meteosat infrared image 06Z 19/02/97



FASTEX IOP17 Low 41 03Z 20/02/97 - 15Z



IOP17 - LOW 41 17-20 FEB 1997

The "FASTEX CYCLONE": explosively deepening col wave

Lowest pressure of any cyclone observed by FASTEX

Observations :

Aircraft: Upstream: Learjet (Objective), G-IV Two flights (Objective and Subjective)

MSA: G-IV, UK C-130 (flight no A518, 55 sondes), P-3

Ships: 3 (measuring at 1.5 hourly intervals) + Labrador Sea experiment

Additional soundings: Upstream North America, Europe coastal

Meteorology of Interest :

Two alternative regions of development (similar to IOP11)

Already closed isobars on entering North Atlantic sector

Very pronounced E-W orientated frontal zone in early stages

Strong vertical velocities, and vorticity maximum achieved at early time

LAM gives large areas of negative PV in upper troposphere.

Rapid deepening: 40mb in 24 hours

Pronounced, well sampled, dry intrusions

Minimum height of PV=2 surface = 4.1km

Very active cold front crossing UK causing some severe weather, associated with less-developed secondary system

Data and forecasts:

Excellent cross-sectional data bank showing warm front, warm sector, and cold front

LAM forecasts reasonable at short range, although second low erroneously developed in the 48 hour forecast

Good connection between MSA and upstream flights

Positive impact on ECMWF forecasts by inclusion of dropsonde data from Objective G-IV flight, and radiosonde data from ships and land stations in North America

Model analysis does not develop sufficiently

IOP17 - LOW 41 17-20 FEB 1997

The "FASTEX CYCLONE": explosively deepening col wave

Lowest pressure of any cyclone observed by FASTEX

Observations :

Aircraft: Upstream: Learjet (Objective), G-IV Two flights (Objective and Subjective)

MSA: G-IV, UK C-130 (flight no A518, 55 sondes), P-3

Ships: 3 (measuring at 1.5 hourly intervals) + Labrador Sea experiment

Additional soundings: Upstream US, Europe coastal

Meteorology of Interest :

Two alternative regions of development (similar to IOP11)

Already closed isobars on entering North Atlantic sector

Very pronounced E-W orientated frontal zone in early stages

Strong vertical velocities, and vorticity maximum achieved at early time

LAM gives large areas of negative PV in upper troposphere.

Rapid deepening: 40mb in 24 hours

Pronounced, well sampled, dry intrusions

Minimum height of PV=2 surface = 4.1km

Very active cold front crossing UK causing some severe weather, associated with less-developed secondary system

Data and forecasts:

Excellent cross-sectional data bank showing warm front, warm sector, and cold front

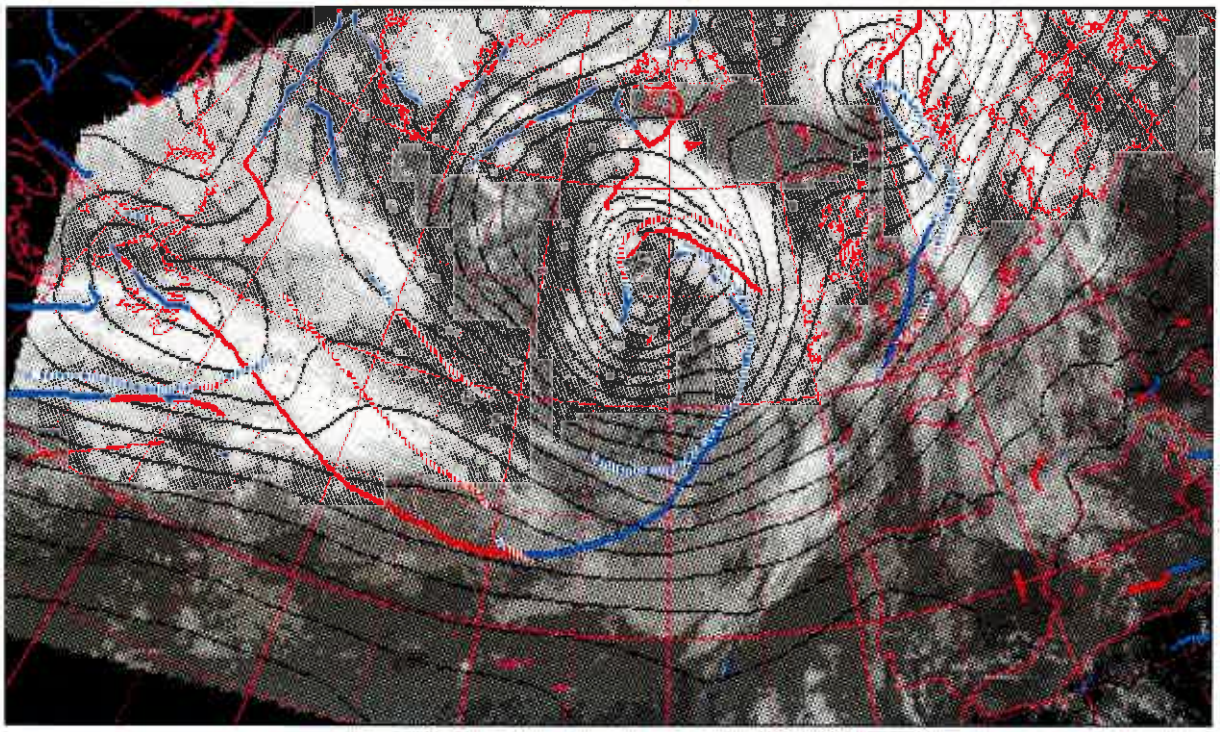
LAM forecasts reasonable at short range, although second low erroneously developed in the 48 hour forecast

Good connection between MSA and upstream flights

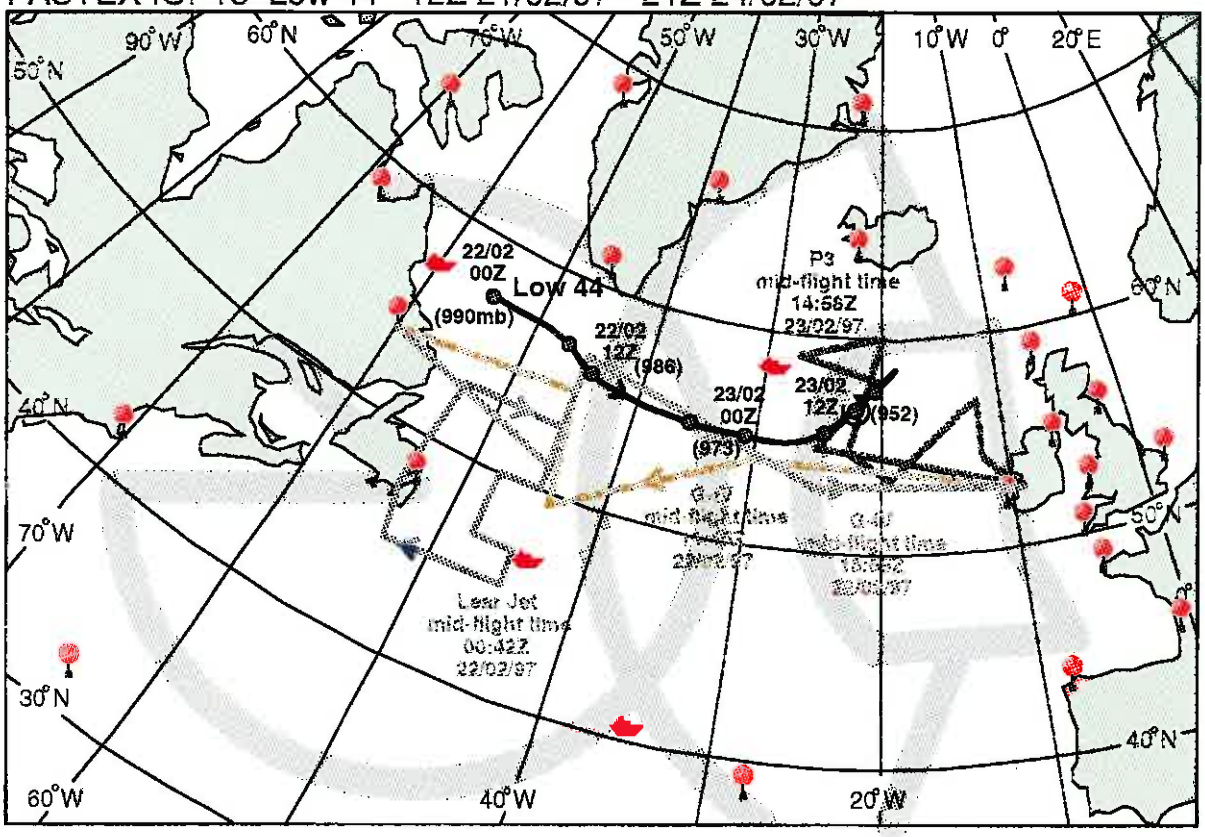
Positive impact on ECMWF forecasts by inclusion of dropsonde data from Objective G-IV flight, and radiosonde data from ships and land stations in US

Model analysis does not develop sufficiently

FASTEX IOP 18 Meteosat infrared image 12Z 23/02/97



FASTEX IOP18 Low 44 12Z 21/02/97 - 21Z 24/02/97



IOP18 - LOW 44 21-24 FEB 1997

Good life-cycle coverage of explosive cyclonic development

Unusual initial conditions: cold unstable air, weak low level thermal gradients

Analogous to a polar low?

Observations :

Aircraft: FUS: Lear Jet, G-IV

NUS: G-IV (second flight)

MSA: P3 with dropsondes

Ships: 2 - 3 + Labrador Sea experiment

Additional soundings: Canada, UK

Meteorology of Interest :

Development associated with marked upper level anomaly (i.e. similar to IOPs 4 & 12; differs from IOPs 11 and 17)

Lowest 'tropopause height' observed during FASTEX (2.7km), associated with considerable Q-G forcing

Quite well forecast by LAM

Mesoscale structure of convective vortices not captured by LAM (50-80kt surface winds)

Fronts most intense at upper levels, developed downwards through evolution

G-IV Labrador sea transects, through cold outflow from ice edge (+Knorr)

Widespread convection; sampled by P3 radar

Well suited to validation of convective air mass modification

Limitations :

P3 radar data awaited

Only 23 MSA sondes

Very complex, rapidly evolving (objective) frontal structure

IOP18 - LOW 44 21-24 FEB 1997

Good life-cycle coverage of explosive cyclonic development

Unusual initial conditions: cold unstable air, weak low level thermal gradients

Analogous to a polar low?

Observations :

Aircraft: FUS: Lear Jet, G-IV

NUS: G-IV (second flight)

MSA: P3 with dropsondes

Ships: 2 - 3 + Labrador Sea experiment

Additional soundings: Canada, UK

Meteorology of Interest :

Development associated with marked upper level anomaly (i.e. similar to IOPs 4 & 12; differs from IOPs 11 and 17)

Lowest 'tropopause height' observed during FASTEX (2.7km), associated with considerable Q-G forcing

Quite well forecast by LAM

Mesoscale structure of convective vortices not captured by LAM (50-80kt surface winds)

Fronts most intense at upper levels, developed downwards through evolution

G-IV Labrador sea transects, through cold outflow from ice edge (+Knorr)

Widespread convection; sampled by P3 radar

Well suited to validation of convective air mass modification

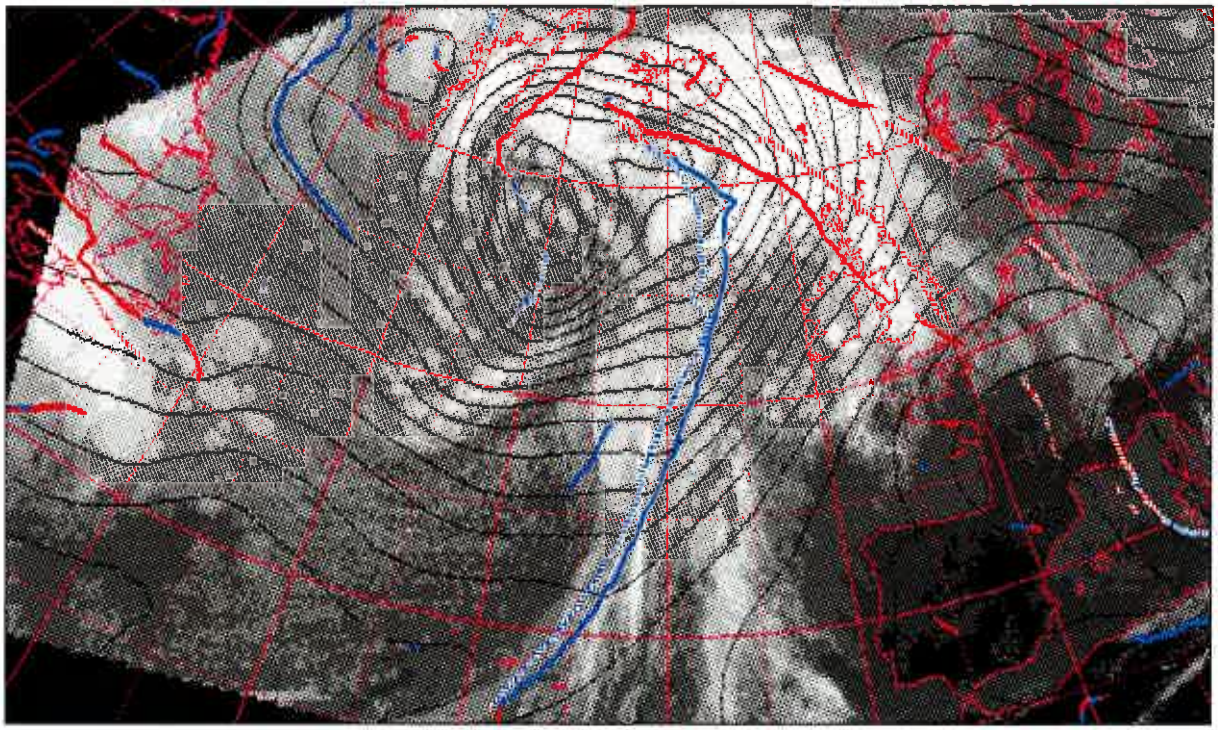
Limitations :

P3 radar data awaited

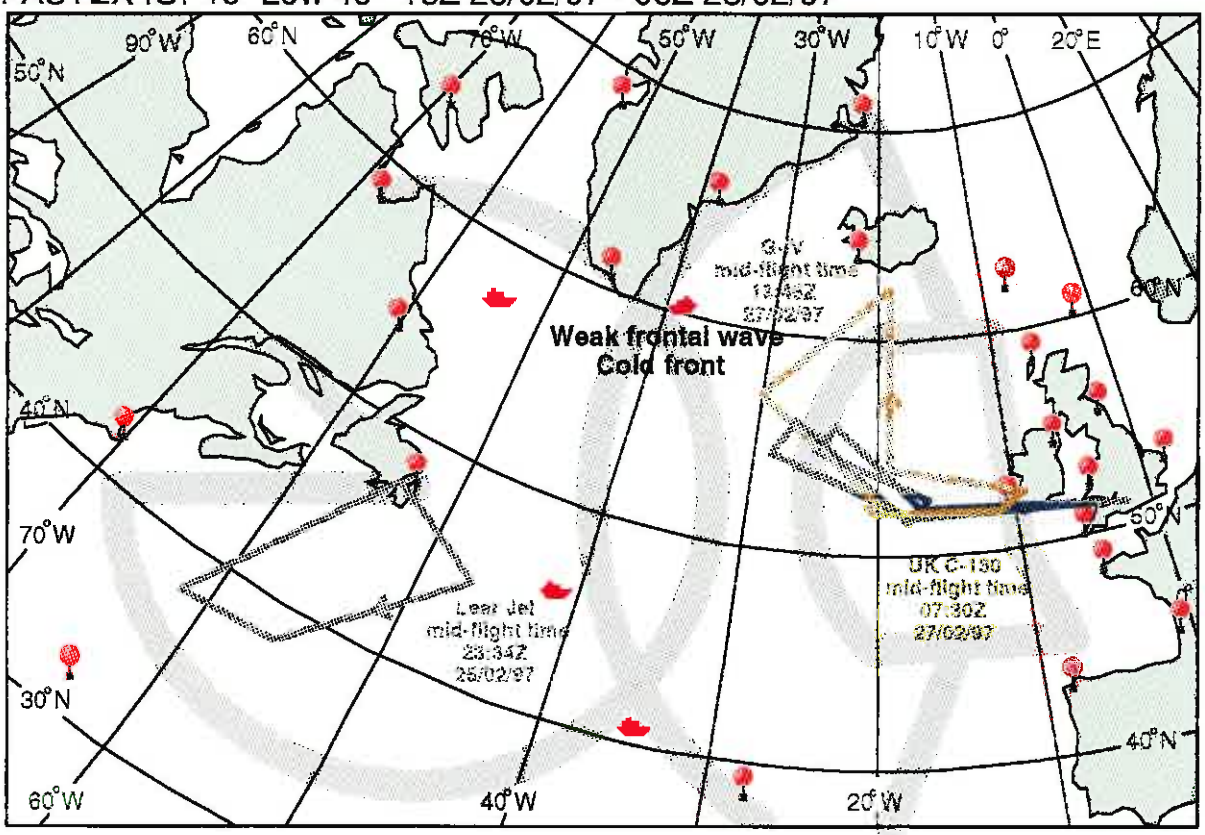
Only 23 MSA sondes

Very complex, rapidly evolving (objective) frontal structure

FASTEX IOP 19 Meteosat infrared image 12Z 27/02/97



FASTEX IOP19 Low 46 18Z 25/02/97 - 06Z 28/02/97



The system was a very weak open wave (low 46) on the trailing cold front of a deep primary cyclone (low 45)

Observations :

Aircraft: FUS: Lear jet

MSA: UK-C-130 (flight no A520, 60 sondes), G-IV (50 sondes)

Ships: 2 + Labrador Sea experiment

Additional soundings: Upstream North America, Europe coastal

Meteorology of Interest :

Decaying wave, good null case analogous to IOP 7 (question of why wave decayed)

Upper PV anomaly

Sferics detected

Long UK C-130 sections through multiple cold fronts

The Lear jet sampled the trough precursor using (NRL/NCEP targets)

Despite the weakness of the system, the ECMWF 36 hour forecast overdeveloped the low, and misplaced the resulting centre

Limitations :

Military exclusion zone compromised the MSA flights

No supporting Doppler radar data

IOP 19 - LOW 46 25-28 FEB 1997

The system was a very weak open wave (low 46) on the trailing cold front of a deep primary cyclone (low 45)

Observations :

Aircraft: FUS: Lear jet

MSA: UK-C-130 (flight no A520, 60 sondes), G-IV (50 sondes)

Ships: 2 + Labrador Sea experiment

Additional soundings: Upstream US, Europe coastal

Meteorology of Interest :

Decaying Wave, good null case analogous to IOP 7 (question of why wave decayed)

Upper PV anomaly

Sferics detected

Long UK C-130 sections through multiple cold fronts

The Lear jet sampled the trough precursor using (NRL/NCEP targets)

Despite the weakness of the system, the ECMWF 36 hour forecast overdeveloped the low, and misplaced the resulting centre

Limitations :

Military exclusion zone compromised the MSA flights

No supporting Doppler radar data

3. IOP OVERVIEW TABLES

The tables were generated to produce a compact summary of the essential features of each case in a way which facilitates intercomparison. The contents of the overview tables were largely based upon analyses and forecasts from the UK Met. Office LAM. The fields were available at a slightly degraded resolution of ~100km in the horizontal, and 100mb in the vertical (the domain is that used for the IR/fronts composite images in section 2). This was considered adequate for most of the purposes of interest here, at least for preliminary studies.

The following tables are included:

1. Basic information
2. Morphology
3. Development
4. Tropopause structure
5. Diabatic processes
6. Fronts
7. Forecast accuracy
8. JCMM overall evaluation

Tables 1 to 4 are straightforward and self-explanatory. Constructing tables 5 to 7 was rather more involved; supplementary information is provided below in (a), (b) and (c). Table 8 was determined purely by a total of subjective votes, and is given mainly to indicate the priorities of cases in JCMM research studies.

Entries are missing from some of the table cells because information was not available for some cases or was inappropriate; for example, many quantities are difficult to characterise for weaker developments.

a) Diabatic Processes

Diabatic processes (primarily latent heat transfers associated with condensation, sublimation or melting) in a weather system are best evaluated in terms of their influence upon the PV distribution and hence the dynamical structure of the system. Heating (cooling) within the body of the atmosphere has associated with it increased (decreased) PV and static stability below and decreased (increased) PV and static stability above the level of heating, which are evident in model fields. (In the case of PV, however, the terms "above" and "below" are approximate and must be properly construed in a 3-dimensional sense consistent with the full production term and thermal gradients, not simply the geometric vertical.)

The main heating level is typically around 700mb, near the maximum of w dq(sat)/dz; an upper level minimum near the tropopause in jet cores and a low level maximum near developing centres are typical signatures in model PV fields. The detailed distribution of PV changes will be significantly affected by the model's parametrizations of moist adjustment processes.

b) Fronts

1] This table was filled in using LAM objective front analyses (Hewson, 1996). Surface and upper fronts are based on θ_w fields from, respectively, the 900mb and 600mb levels. Frontal slope refers to the layer between these levels; use of the words "forward sloping" in the table implies an overrunning upper front.

2] Entries correspond to time/location of any MSA flights. If no MSA flights then entries correspond to the time/location of the last flight by any aircraft.

3] 'Primary' means the MOST PROMINENT front of a particular type - this would be expected to lie in a semi-classical location relative to low/wave centre.

4] 'Secondary' means the SECOND MOST PROMINENT front of a particular type - it may be anywhere relative to the primary front, but must show some connection with the low in question. It will usually be nearly-parallel to the primary front, ahead of it or to the rear.

5] 'Standard' objective fronts are those which approximate to manually drawn fronts; 'weak' objective fronts are those recognised only when the cut-off thermal gradient threshold criteria applied to obtain standard fronts have been halved. Whether a front is classified Weak or Standard depends on what category MOST of that front falls into.

6] 'Ana-' and 'Kata-' characteristics were determined according to whether the total quasi-geostrophic forcing (Clough et al, 1996) along the fronts in question was, respectively, positive (=ascent) or negative (=descent). Whether a front is classified 'Ana' or 'Kata' depends on what category MOST of that front falls into.

7] A 'Warm-conveyor-belt front' is defined to be an objective surface (warm) front that is found ahead of and nearly parallel to an objective cold front. As such it is distinct from a secondary warm front.

c) Good/moderate/poor forecast definitions

UKMO model forecasts for the lows which were subject to FASTEX IOPs have been evaluated using, for each IOP, one validating time which corresponded to when the low was over or close to the MSA. Two parameters have been assessed: the position error (separation of forecast and actual low centres) and pressure error (pressure at centre of forecast low minus pressure at centre of actual low). Each error in these two categories has been classified as Good (green), Moderate (orange) or Poor (red) according to whether, relative to the population, the error was in the category containing, respectively, the best 60% of forecasts, the next best 30%, or the worst 10% (thresholds are given in the table below). By "population" we mean forecasts for lows occurring in the north Atlantic region during the previously analysed pre-FASTEX period (February and March 1996). The "population" does not include the FASTEX period itself.

Good position forecast (60% of cases)	T+24 T+48 T+72 T+96 T+120	True low lies within	0-150km 0-250km 0-350km 0-500km 0-650km
Moderate position (30%)	T+24 T+48 T+72 T+96 T+120	True low lies within	150-350km 250-550km 350-750km 500-950km 650-1150km
Poor position (10%)	T+24 T+48 T+72 T+96 T+120	True low lies at	>350km >550km >750km >950km >1150km
Good pressure forecast (60%)	T+24 T+48 T+72 T+96 T+120	Central pressure error magnitude	<=3mb <=5mb <=7mb <=9mb <=11mb
Moderate pressure forecast (30%)	T+24 T+48 T+72 T+96 T+120	Central pressure error magnitude	3-6mb 5-10mb 7-13mb 9-17mb 11-21mb
Poor pressure forecast (10%)	T+24 T+48 T+72 T+96 T+120	Central pressure error magnitude	>6mb >10mb >13mb >17mb >21mb

Acknowledgement

We are grateful to Rachael Norwood for her help in the preparation and production of this report.

REFERENCES

Clough, S A, C S A Davitt and A J Thorpe	1996	Attribution concepts applied to the omega equation. *Q.J.R. Meteorol. Soc. 122, 1943-1962*
Hewson, T D	1996	Objective Fronts. *JCMM Internal Report 57;* *Met. Apps. 1998,* to appear
Joly, A, D Jorgensen, M A Shapiro, A Thorpe, P Bessemoulin, K A Browning, J-P Cammas, J-P Chalon, S A Clough, K A Emanuel, L Eymard, R Gall, P H Hildebrand, R H Langland, Y Lemaitre, P Lynch, J A Moore, P Ola G Persson, C Snyder and R M Wakimoto	1997	The Fronts and Atlantic Storm Track Experiment (FASTEX): Scientific Objectives and Experimental Design. *Bull. Amer. Meteor. Soc.*
Jorgensen, D, P Bessemoulin, S A Clough and J Moore, eds.	1996	Fronts and Atlantic Storm Track Experiment (FASTEX) Operations Plan. CNRM/PAD, 2 Ave. Rapp, 75340 Paris CEDEX 07 France

Table 1: Basic Information

IOP Number	Cyclone?	Subjective Classification	MAX no. of 1mb interval closed isobars attained*	Low centre position for MAX	Date/time for MAX	Diameter of largest closed isobar at MAX (km)	System Speed ms^{-1}/Direction (towards) deg**	MSA flight start/end times***
IOP 1	Yes	Wave cyclone	3	55N, 20W	09Z 10/1	500	22/ 040	01Z - 11Z 10/1
IOP 2	No	Warm Sector Wave	-	-	-	-	30/ 040	11Z - 21Z 12/1
IOP 4	Yes	Cold Air Comma Cloud	6	48N, 22W	15Z 17/1	700	7/ 060	G-IV 10Z - 14Z 17/1
IOP 5	No	Col within high pressure region	2	47N, 18W	12Z 22/1	450	?/070 (hard to define low centre)	06Z - 16Z 22/1
IOP 6	No	Cold Front	-	-	-	-	22/090	G-IV: 16Z 23/1 - 00Z 24/1
IOP 7	Maybe	Flat wave in deformation zone	0	-	-	-	23 /050	21Z 25/1 - 05Z 26/1
IOP 8	No	Greenland Lee Waves	0	-	-	-	-	-
IOP 9	Yes	Mature low - two deepening phases	16	60N, 23W	00Z 3/2	1000	19/060	16Z - 23Z 2/2
IOP 10	No	Flat Wave	-	-	-	-	Inconsistent forecasts	06Z - 15Z 4/2
IOP 11	Yes	Large developing cyclone	17	64N, 6W	15Z 6/2	900	31/ 045	19Z 5/2 - 06Z 6/2

IOP Number	Cyclone?	Subjective Classification	MAX no. of 1mb interval closed isobars attained*	Low centre position for MAX	Date/time for MAX	Diameter of largest closed isobar at MAX (km)	System Speed ms^{-1}/Direction (towards) deg**	MSA flight start/end times***
IOP 11a	Yes	Developing Secondary Cold Front Wave	5	56N, 17W	15Z 8/2	400	23/040	G-IV 11Z - 12Z 8/2
IOP 12	Yes	Explosive cyclogenesis	16	63N, 26W	06Z 10/2	900	9/040	14Z - 22Z 9/2
IOP 15	Yes	Occluded system	32	53N, 24.5W	18Z 15/2	1600	12/060	08Z - 17Z 15/2
IOP 16	Yes	Frontal Wave	0	61N, 8W	18Z 17/2	250	30/065	04Z - 13Z 17/2
IOP 17	Yes	Explosively deepening col wave	20	62N, 8W	18Z 19/2	600	18/030	02Z - 12Z 19/2
IOP 18	Yes	Explosively deepening cold air vortex	30	57N, 18W	21Z, 23/2	1200	7/080	11Z - 20Z 23/2
IOP 19	No	Open Wave	0	-	-	-	41/ 045	02Z - 15Z 27/2

* at any time when the low centre was south of 65N

** during MSA flight(s), or if no MSA flight then when low centre crosses 30W

*** Times of entry of first MSA aircraft and leaving of last to nearest hour

Table 2: Development

IOP	LOCATION	LOW LEVEL DEVELOPMENT observed between 50W and 30W					UPPER LEVEL CONNECTION observed up to 20 deg west of surface feature			RATE OF DEVELOPMENT Surface deepening rate	
	Location of low centre when 4mb interval closed isobar first appears	Is the Low developing on a frontal zone?	If so, was this front trailing from a parent cyclone?	Length of 900mb relative vorticity zone > $1.5x10^{-4}s^{-1}$ in the along front direction (deg. lat)	Max 900mb relative vorticity in the low ($x10^{-4}s^{-1}$)	Max 900mb PV in the low (PVU)	Is there a trough axis in the 315K PV distribution?	If so, how far west of the surface feature is the trough axis? (deg long)	What is the approx meridional extent of the trough (deg lat)	WEST (50W-30W) mb/day equivalent	EAST (30W-10W) mb/day equivalent
1	54N, 20W	Yes	No	-	1.2	0.4	Yes	23	25	0	0
2	-	Yes	No	-	-	-	-	-	-	-	-
4	48N, 22.5W	No	-	-	1.4	0.6	Yes	2	8	0	0
5	48N 18W	Yes	Yes	4	1.7	0.8	Yes	1	8	-	Open wave
6	-	-	-	-	2.0	1.0	Yes	5	25	-	-
7	-	Yes	No (in col region)	-	0.8	0.7	Yes (2)	5	30	-	0
9	Beyond domain (to the SW)	Yes (probably)	No (probably)	?	2.4	2.4	No (probably)	-	-	7	21

10	-	Yes	Yes	-	0.3	0.5	Yes	5	2	-	-
11	-	No	No	8	2.4	1.1	Yes	9	12	28	13
11a	54N, 20W	Yes	Yes	-	1	0.7	Yes	5	18	4	11
12	57N, 27W	Yes	Yes	3	2.2	1.1	Yes	20	5	-	28
15	Beyond domain (to the SW)	Yes	No	7	2.9 (just)	1.6	Yes	0	20	16	0
16	-	Yes	Yes	-	1.5×10^{-4} (just)	1.3	Yes but very broad	8	8	-	18
17	Beyond domain (to the SW)	Yes	No	12	3.9 (just)	1.6	Yes	6	13	30	40
18	57N, 46W	No	-	-	0.9	0.4	No (jet instead)	-	-	18	44
19	-	Maybe	Yes	6	2.2	1.1	Yes	10	12	-	-

Table 3: Morphology

900mb winds above 25m/s are indicated in**Bold**

IOP	Frontal Fracture?	700mb vertical velocity			Thunderstorms or Strong Convection?	Cloud Head?	Dry Intrusion(s) in WV imagery?	Max wind at 900mb (ms^{-1})*
		>5cms^{-1}?	Maximum Value (cms^{-1})	Dimensions (major x minor axes) of 10cms^{-1} contour (deg lat)*				
1	Possibly	Yes	16	6 x 2	No Sferics available	Yes	Yes (excellent)	**25**
2	No	Yes	9	-	Sferics west of MSA	Yes	Yes	**29**
4	No	Yes	7	-	Yes (Sferics present)	Yes	Yes	20
5	Yes	Yes	10	0.1 x 0.1	No	Yes	Yes	16
6	No	Yes	10	1 x 0.5	No Sferics or imagery available	No imagery available	No imagery available	**28**
7	No	No	3	-	No Sferics (Up to 0.2mm/hour convective rainfall in model)	No	No (Maybe around 30W on G-IV flight)	13
9	No (possibly beyond domain to the west)	Yes	16 (28@55W)	3.5x1.5 (7x4@55W)	Yes (FUS only)	Yes	Yes (limited)	**32 (38@45W)**
10	No	Yes	6	-	Imagery missing, narrow squall line observed by P3	No	Yes	22
11	No	Yes	10	2 x 1	No	No	No	**36**

11a	Possibly	Yes	10	2.5 x 1	Yes (12-24 hrs before G-IV flight	Yes. Possibly multiple	In classical location as low develops	**38**
12	No	Yes	16	6 x 2	Yes (very active)	Yes	Yes	**33**
15	Yes	Yes	24	6 x 3	Yes	Yes	No	**30**
16	Yes	Yes	13	6 x 2	No	Yes	Yes	**40**
17	Yes	Yes	30	6 x 2	Yes (Sferics on and behind cold front)	Yes	Yes	**42**
18	No	Yes	19	10 x 2	Yes (on & behind primary cold front)	No	Yes (fragmented, develops south of low)	**34**
19	No	Yes	8	-	Yes	No	No	**34**

IOP	**Frontal Fracture?**	**700mb vertical velocity**			**Thunderstorms or Strong Convection?**	**Cloud Head?**	**Dry Intrusion(s) in WV imagery?**	**Max wind at 900mb (ms^{-1})***
		> 5cms^{-1}?	**Maximum Value (cms^{-1})**	**Dimensions (major x minor axes) of 10cms^{-1} contour (deg lat)***				

* Max Values given for MSA period but max value during whole life cycle may be added in brackets.

Table 4: Tropopause Structure

IOP	Trop fold on PV=1.5 PVU?	PV=2			PV on 500mb Surface	
		MIN Ht (km)*	Time of MIN	Position of MIN at this time	MAX Value (PVU)*	Time of MAX value
1	No	6	9Z 10/1	45N, 25W	1.2	9Z 10/1
2	No (Lear flight)	5	15Z 12/1	52N, 27W	2.0	15Z 12/1
4	No	6	(No clear min time)		1.2	9Z 17/1
5	No	6.4	12Z 22/1	46N, 22W	1.2	12Z 22/01
6	Yes	3	21Z 23/1	57N, 20W	3.5	21Z 23/1
7	Yes (G-IV flight)	5.5	18Z 25/1	56N, 30W	1.8	21Z 25/1
9	No?	7.0	12Z 2/2	55N, 38W	1.5	12z 2/2
10	No	6.5	12Z 4/2	55N, 10W	1.0	9Z-12Z 4/2
11	No	5	21Z 5/2	40N, 35W	2.4	21Z 5/2
11a	No	7	12Z 08/2	53N, 25W	1.0	12Z 08/2
12	Yes	4.6	15Z 9/2	52N, 37W	2.6	15Z 09/2
15	No	4.1	00Z 15/2	50N, 33W	3.2	00Z 15/2
16	Yes (Lear flight)	5.5	11Z 17/2	54N, 29W	1.7	9Z 17/2
17	Yes (Lear flight)	4.1	09Z 18/2	37N, 53W	3.1	18Z 18/2

IOP	Trop fold on PV=1.5 PVU?	PV=2 height			PV on 500mb Surface	
		MIN Ht (km)*	Time of MIN	Position of MIN at this time	MAX Value (PVU)*	Time of MAX value
18	Yes	2.7	00Z 22/2	53N, 62W	4.0	00z 22/2
19	Yes (not within flights)	4.1	03Z 27/2	57N, 30W	1.7	15Z 27/2

* Before end of MSA observations

** range of highest to lowest value of minimum height attained during the IOP

Table 5: Diabatic Processes

See Section 3a for an explanation of the significance of the quantities tabulated here.

IOP	900mb		500mb				300mb			
			Downstream		Upstream		Downstream		Upstream	
	Max PV within low (PVU)*	Distance from low centre to maximum (km)	Min PV value within 500km downstream of low centre (PVU)*	Distance from low centre to minimum (km)	Min PV value within 500km upstream of low centre (PVU)*	Distance from low centre to minimum (km)	Min PV value within 500km downstream of low centre (PVU)*	Distance from low centre to minimum (km)	Min PV value within 500km upstream of low centre (PVU)*	Distance from low centre to minimum (km)
1	1.4	75	**0.1**	500	0.1	450	**-0.2**	400	**-1.0**	400
2	1.0	-	0.2	**450**	-	-	-0.3	500	-	-
4	0.5	0	**0.3**	200	0.4	500	**0.0**	400	-	-
5	**0.8**	0	-	-	-	-	-	-	-	-
6	1.0	-	0.2	**450**	0.2	450	-0.3	300	0	300
7	No maximum	No centre	0.2	350	-	-	0.3	500	-	-
9	2.7	200	0.2	500	0.2	100	-0.4	500	0.7	450
10	0.8	No centre	**0**	200	0.1	200	0.3	100	-	-
11	0.8	No centre	0.4	500	-	-	-0.1	500	-	-

11a	0.7	50	-	-	-	-	0.8	300	-	-
12	1.3	?	0	500	-	-	-0.1	500	0	-
15	1.6	500	0.2	**500**	-	-	-0.3	**500**	-	-
16	0.9	100	**0.2**	200	-	-	**-0.2**	500	**0**	400
17	1.7	50	**0.2**	500	-0.3	500	**-0.5**	450	**-0.3**	100
18	**1.1**	100	**0.0**	400	**>0.3**	150	**0.5**	500	**4**	150
19	1.2	?	-	-	-	-	-	-	-	-

IOP	900mb		500mb				300mb			
			Downstream		Upstream		Downstream		Upstream	
	Max PV within low (PVU)*	Distance from low centre to maximum (km)	Min PV value within 500km downstream of low centre (PVU)*	Distance from low centre to minimum (km)	Min PV value within 500km upstream of low centre (PVU)*	Distance from low centre to minimum (km)	Min PV value within 500km downstream of low centre (PVU)*	Distance from low centre to minimum (km)	Min PV value within 500km upstream of low centre (PVU)*	Distance from low centre to minimum (km)

* Before end of MSA obs. **Bold** if within area of MSA aircraft obs.

Table 6: Fronts

Section 3b provides definition of terms used

Key: S=Standard, W=Weak, A=Ana, K=Kata

IOP	Primary Warm Front			Secondary Warm Front			warm conveyor belt front?	Primary Cold Front			Secondary Cold Front		
	Upper Front	Surface Front	Slope	Upper Front	Surface Front	Slope		Upper Front	Surface Front	Slope	Upper Front	Surface Front	Slope
1	-	S,A	1:70	-	S,A	-	Yes	S,A	S,A	1:60 (forward sloping)	-	-	-
2	S,A	S,A	1:27	S,A	S,A	1:17	No	-	-	-	-	-	-
4	-	W,A	-	-	-	-	Yes	W,A	W,A/K	1:15 (forward sloping)	-	-	-
5	S,A	S,A	1:37	-	-	-	Yes	S,A	S,K	1:62	-	-	-
6	S,A	S,A	1:75	S,K	S,A	1:30	No	-	-	-	-	-	-
7	-	S,A	-	-	-	-	Yes (weak)	S,A	S,A	1:57	S,A	-	-
9	S,A	S,A	1:38	-	-	-	Yes	S,K	S,K	1:38 (forward sloping)	S,A	W,A	Vertical
10	S,A	S,A	1:50	-	-	-	Yes	S,A	S,K	1:25	-	-	-
11	S,A	S,A	1:42	S,A	S,A	1:70	No	S,A	S,A	1:42	-	-	-
11a	S,A	S,A	1:5	S,A	S,K	1:43 variable	No	-	-	-	W,K	-	-
12	S,A	S,A	1:35	-	-	-	-	S,A	W,A	-	-	-	-

15	S,A	S,A	1:30 (forward sloping)	S,A	S,A	Vertical	No	-	-	-	-	-	-
16	S,A	S,A	1:50	-	-	-	Yes	S,A	S,K	1:25	-	-	-
17	S,A	S,A	1:47	S,A	S,A	1:19	No	S,A	S,K	1:10(forward sloping)	-	-	-
18	S,A	W,A	1:31	-	S,A	-	Yes(2)	S,A	W,A	1:14 (forward sloping)	S,K	W,K	Vertical
19	-	-	-	-	-	-	No	S,A	S,A	1:35	-	S,A	-
IOP	**Primary Warm Front**			**Secondary Warm Front**			**warm conveyor belt front?**	**Primary Cold Front**			**Secondary Cold Front**		
	Upper Front	**Surface Front**	**Slope**	**Upper Front**	**Surface Front**	**Slope**		**Upper Front**	**Surface Front**	**Slope**	**Upper Front**	**Surface Front**	**Slope**

Table 7: Forecast Accuracy

See Section 3c for supplementary information.

UKMO Forecasts, for IOP low centres, are colour coded to show forecast accuracy:

GOOD Forecasts: GREEN MODERATE Forecasts: ORANGE POOR Forecasts: RED

Definition of Good,moderate,poor

Supplementary comments: DARK RED

Positive pressure errors (=insufficient depth) are shown bold

Note that for IOPs 2, 6, 8 and 19 there was no real low centre to verify.

IOP	T+24 (LAM)		T+48 (LAM)		T+72 (Global)		T+96 (Global)		T+120 (Global)	
	Position Error (km)	PMSL Error (mb)	Position Error (km)	PMSL Error (mb)	Position Error (km)	PMSL Error (mb)	Position Error (km)	PMSL Error (mb)	Position Error (km)	PMSL Error (mb)
1	150	-6	250	-1	No closed low	No closed low	No closed low	No closed low	-	-
2	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	450	**+20**	350	**+29**	No low	No low
4	100	-4	400	+1	200	+4	900	+9	1300	+4

5	440	0	990	-2	200	+3	Trough not low	Trough not low	Wrong structure	Wrong structure
6	-	-	-	-	-	-	-	-	-	-
7	140	+1	160	-6	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-
9	130	-4	20	-8	60	0	850	+11	600	+13
10	500	-17	500	-17	600	-12	1000	-20	No appropriate low	No appropriate low
11	280	0	280	-3	400	-3	700	-8	1100	+13
11a	140	**+8**	110	+6	350	+10	250	+14	No appropriate low	No appropriate low
12	100	**+7**	330	**+20**	350	**+32**	650	**+41**	No appropriate low	No appropriate low
13	500	-9	700	-1	600	+8	850	+12	1600	+14
14	300	+2	200	-3	1300	+7	200	0	150	-13
15	70	-2	0	-9	150	+5	550	-6	700	0
16	100	-5	250	-5	250	+11	No low	No low	250 (different low?)	+19 (different low?)
17	180	**+7**	800	**+17**	300	**+25**	1250 (double centre)	**+31** (double centre)	1150	**+49**
18	60	-1	170	+5	100	+3	750	+11	600	**+26**
19	Good	Moderate	Good	Moderate	-	-	-	-	-	-

CURRENT JCMM INTERNAL REPORTS

This series of JCMM Internal Reports, initiated in 1993, contains unpublished reports and also versions of articles submitted for publication. The complete set of Internal Reports is available from the National Meteorological Library on loan, if required.

1. **Research Strategy and Programme**
   K A Browning et al
   January 1993

2. **The GEWEX Cloud System Study (GCSS)**
   GEWEX Cloud System Science Team
   January 1993

3. **Evolution of a mesoscale upper tropospheric vorticity maximum and comma cloud from a cloud-free two dimensional potential vorticity anomaly**
   K A Browning
   January 1993

4. **The Global Energy and Water Cycle**
   K A Browning
   July 1993

5. **Structure of a midlatitude cyclone before occlusion**
   K A Browning and N Roberts
   July 1993

6. **Development in Systems and Tools for Weather Forecasting**
   K A Browning and G Szejwach
   July 1993

7. **Diagnostic study of a narrow cold frontal rainband and severe winds associated with a stratospheric intrusion**
   K A Browning and R Reynolds
   August 1993

8. **Survey of perceived priority issues in the parametrizations of cloud-related processes in GCMs**
   K A Browning
   September 1993

9. **The Effect of Rain on Longwave Radiation**
   I Dharssi
   September 1993

10. **Physical Cloud Microprocesses - A Description of the Parametrization used in the Large Eddy Model**
    H Swann
    July 1994

11. **An Appreciation of the Meteorological Research of Ernst Kleinschmidt**
A J Thorpe
May 1992

12. **Potential Vorticity of Flow Along the Alps**
A J Thorpe, H Volkert and Dietrich Heimann
August 1992

13. **The Representation of Fronts**
A J Thorpe
January 1993

14. **A Parametrization Scheme for Symmetric Instability: Test for an Idealised Flow**
C S Chan and A J Thorpe
February 1993

15. **The Fronts 92 Experiment: a Quicklook Atlas**
Edited by T D Hewson
November 1993

16. **Frontal wave stability during moist deformation frontogenesis**
Part 1. Linear wave dynamics
C H Bishop and A J Thorpe
May 1993

17. **Frontal wave stability during moist deformation frontogenesis**
Part 2. The suppression of non-linear wave development
C H Bishop and A J Thorpe
May 1993

18. **Gravity waves in sheared ducts**
C Bishop and A J Thorpe
November 1993

19. **Potential Vorticity and the Electrostatics Analogy: Quasi-Geostrophic Theory**
C Bishop and A J Thorpe
November 1993

20. **Recent Advances in the Measurement of Precipitation by Radar**
A J Illingworth
April 1993

21. **Micro-Physique et Givrage. Cloud Microphysics and Aircraft Icing**
A J Illingworth
May 1993

22. **Differential Phase Measurements of Precipitation**
M Blackman and A J Illingworth
May 1993

23. **Estimation of Effective Radius of Cloud Particles from the Radar Reflectivity**
N I Fox and A J Illingworth
May 1993

24. **A Simple Method of Dopplerising a Pulsed Magnetron Radar**
A Hau, A J Illingworth and J Eastment
November 1993

25. **Radiation and Polar Lows**
George C Craig
February 1994

26. **Collected preprints submitted to the International Symposium on the Life Cycles of Extratropical Cyclones; Bergen, Norway, 27 June - 1 July 1994**
April 1994

27. **Convective Frontogenesis**
Douglas J Parker and Alan J Thorpe
April 1994

28. **Improved Measurement of the Ice Water Content in Cirrus Using a Total Water Evaporator**
Philip R A Brown and Peter N Francis
April 1994

29. **Mesoscale Effects of a Dry Intrusion within a Vigorous Cyclone**
K A Browning and B W Golding
April 1994

30. **GEWEX Cloud System Study, Science Plan**
May 1994

31. **Parametrization of Momentum Transport by Convectively Generated Gravity Waves**
R Kershaw
February 1995

32. **Mesoscale Modelling Newsletter No 5**
May 1994

33. **Observations of the mesoscale sub-structure in the cold air of a developing frontal cyclone**
K A Browning, S A Clough, C S A Davitt, N M Roberts and T D Hewson
May 1994

34. **Longwave Radiative Forcing of a Simulated Tropical Squall Line**
Imtiaz Dharssi
July 1994

35. **On the nature of the convective circulation at a kata-cold front**
K A Browning
September 1994

36. **Collective preprints of papers submitted to the COST-75 International Seminar on Advanced Weather Radar Systems, Brussels, 20-23 September 1994**
November 1994

37. **Use of satellite imagery to diagnose events leading to frontal thunderstorms: Parts 1 and 11 of a case study**
K A Browning and N M Roberts
November 1994

38. **The role of spaceborne millimetre-wave radar in the global monitoring of ice cloud**
P R A Brown, A J Illingworth, A J Heymsfield, G M McFarquahar, K A Browning and M Gosset
December 1994

39. **Potential Vorticity Inversion**
Michael Ziemianski
October 1994

40. **Theory of mature tropical cyclones; a comparison between Kleinschmidt (1951) and Emanuel (1986)**
Suzanne L Gray
December 1994

41. **Dispersion and removal of pollutants during the passage of an atmospheric frontal System**
N R Gimson
December 1994

42. **The role of snow sublimation in frontogenesis**
D J Parker and A J Thorpe
December 1994

43. **Potential vorticity and the electrostatics Analogy: Ertel- Rossby formulation**
A J Thorpe and C H Bishop
December 1994

44. **Mesoscale aspect of extratropical cyclones: an observational perspective**
K A Browning
January 1995

45. **A Polar Low Outbreak: Evolution and Mesoscale Structures**
T D Hewson, G C Craig and C Claud
February 1995

46. **Generation of near-surface gusts of deep convection**
K Nakamura and R Kershaw
April 1995

47. **Attribution Concepts applied to the Omega Equation**
S A Clough, C S A Davitt and A J Thorpe
June 1995

48. **Parametrization of mixed-phase cloud and precipitation**
Susan P Ballard and M Gerard Hutchinson
June 1995

49. **Short-range forecasting of stratocumulus: Initialization Prediction**
Susan Ballard, Simon D Jackson and B Macpherson
June 1995

50. **Contributions of the JCMM/Dept of Meteorology Radar Group to the 27th AMS Radar Meteorology Conference, Vail October 1995**
June 1995

51. **Cold Pools in Shear**
Douglas J Parker
September 1995

52. **High-resolution analysis of frontal fracture**
K A Browning, S P Ballard and C S A Davitt
September 1995

53. **The Albedo of Broken Cloud Fields: Calculations using a modified two stream radiation code**
Imtiaz Dharssi and Roy Kershaw
October 1995

54. **Parametrization of momentum transport by convection. I: Theory and cloud modelling results**
R Kershaw and D Gregory
November 1995

55. **Variation of frontal structure along a cold front**
K A Browning and N M Roberts
November 1995

56. **Secondary Frontal Waves**
Douglas Parker
December 1995

57. **Objective Fronts**
T D Hewson
March 1996

58. **Mesoscale analysis of the activation of a cold front during cyclogenesis**
K A Browning, N M Roberts and A J Illingworth
June 1996

59. **Investigation of Different Representations of Rain in a 1-d Evaporation Model**
H Swann
May 1996

60. **Parametrization of diabatic processes in the inversion of the omega-equation**
M Athanassiadou and A J Thorpe
June 1996

61. **The Role of the Environmental Flow in the Development of Secondary Frontal Cyclones**
I A Renfrew, A J Thorpe and A Joly
June 1996

62. **Consequences of the geostrophic momentum approximation on barotropic instability**
S Malardel, A J Thorpe and A Joly
June 1996

63. **Contributions to the AMS/RMS Conference on Mesoscale Processes**
Reading, 9-13 September 1996

64. **Vorticity and Potential Vorticity in Stratified Flows Interacting with an Isolated Obstacle**
Jorge A Gutiérrez and A J Thorpe
September 1996

65. **Triple Point Development: Two Case Studies**
Douglas Parker
September 1996

66. **Radar observations of wind-shear splitting within evolving atmospheric Kelvin-Helmholtz billows**
D Chapman and K A Browning
April 1997

67. **Cold Frontal Structure derived from radar wind profilers**
K A Browning, D Jerrett, J Nash, T Oakley, N M Roberts
May 1997

68. **The dry intrusion and its effect on the frontal, cloud and precipitation structure of extratropical cyclones**
K A Browning - Text of invited special lecture at the Spring Conference of the Meteorological Society of Japan, University of Tsukuba, 22 May 1997

69. **Met. Office Unified Model data, diagnostic graphics programs, and other observational data available from the JCMM through the aegis of the Universities Weather Research Network UWERN.** Plus supplement.
Peter Panagi and Ed Dicks
June 1997

70. **Contributions of the JCMM/Dept of Meteorology Radar Group to 28th AMS Radar Meteorology Conference.** Austin, Texas, September 1997

71. **Sensitivity of short-range weather forecasts to local potential vorticity modifications**
Meral Demirtas and Alan Thorpe
July 1997

72. **Objective identification of frontal wave cyclones**
T D Hewson
August 1997

73. **Attribution and its application to mesoscale structure associated with tropopause folds**
A J Thorpe
September 1997

74. **The Role of the Environmental Flow in the Development of Secondary Frontal Cyclones**
Ian A Renfrew, Alan J Thorpe and Craig H Bishop
September 1997

75. **Potential Vorticity: A short history of its definitions and uses**
Alan J Thorpe and Hans Volkert
September 1997

76. **Superposing Semi-Geostrophic Potential Vorticity Anomalies**
H R Birkett and A J Thorpe
September 1997

77. **Short period forecasting of catchment-scale precipitation. Part 1: the role of Numerical Weather Prediction**
M A Pedder, M Haile and A J Thorpe
September 1997

78. **Verification of the Tracking Technique Used in an Experimental Cloud Motion Wind Inferring System**
Z Wang, K A Browning and G A Kelly
October 1997

79. **A Preliminary Study of Fourier Series Analysis for Cloud Tracking with GOES High Temporal Resolution Images**
Z Wang
October 1997

80. **Analysis of an ex-tropical cyclone after reintensifying as a warm-core extratropical cyclone**
K A Browning, G Vaughan and P Panagi
November 1997

81. **A JCMM overview of FASTEX IOPs**
S A Clough, H W Lean, N M Roberts, H Birkett, J-P Chaboureau, R Dixon, M Griffiths, T D Hewson and A Montani
January 1998

Met Office Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
www.metoffice.com